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Proceedings of a seminar on the present status of vision engineering and the possible effects on criteria for school planning. A discussion by Dr. H. Richard Blackwell on vision engineering is included. Topics of discussion include--(1) broad aspects of the effect of light upon sight, (2) lighting variables and task visibility, (3) lighting variables and direct comfort, and (4) general remarks about illumination standards. Tables on lighting requirements for various tasks, required individual footcandles for No. 2 pencil task, and required weighted footcandles for No. 2 pencil task are included, as well as a paper by Dr. H. Richard Blackwell describing the visual benefits of polarized light. (RH)

SCHOOL CONSTRUCTION RESEARCH REPORT #10
SEMINAR TO DISCUSS THE PRESENT STATUS OF VISION ENGINEERING

FOR

THE DADE COUNTY BOARD OF PUBLIC INSTRUCTION

BY

PANCOAST/FERENDINO/GRAFTON/ARCHITECTS

PURPOSE: TO DISCUSS THE PRESENT STATUS OF VISION ENGINEERING AND THE POSSIBLE EFFECTS ON THE CRITERIA FOR SCHOOL HOUSE PLANNING.

LOCATION: OFFICES OF PANCOAST, FERENDINO, GRAFTON & SKEELS, 2575 SOUTH BAYSHORE DRIVE, MIAMI, FLORIDA

DATE: AUGUST 31, 1964

SPEAKER: DR. H. RICHARD BLACKWELL, DIRECTOR
INSTITUTE FOR RESEARCH IN VISION
OHIO STATE UNIVERSITY, COLUMBUS, OHIO

CURRICULUM VITAE

PERSONAL DATA:

BORN:	JANUARY 16, 1921 IN HARRISBURG, PENNSYLVANIA.
MARRIED:	TO OLIVE G. MORTENSEN ON JUNE 12, 1943.
CHILDREN:	LAIRD R., BORN AUGUST 31, 1945.
	BRYAN R., BORN SEPTEMBER 11, 1949.

EDUCATION:

B.S.	(PHILOSOPHY AND PHYCHOLOGY), HAVERFORD COLLEGE 1941.
A.M.	(PSYCHOLOGY), BROWN UNIVERSITY, 1942
PH.D.	(PSYCHOLOGY), UNIVERSITY OF MICHIGAN, 1947.

EXPERIENCE:

1941-42	RESEARCH ASSISTANT, NATIONAL DEFENSE RESEARCH COMMITTEE, BROWN UNIVERSITY.
1942-43	RESEARCH PSYCHOLOGIST, POLAROID CORPORATION.
1943-45	PROJECT DIRECTOR, NATIONAL DEFENSE RESEARCH COMMITTEE, L.C. TIFFANY FOUNDATION.
1945-58	MEMBER OF FACULTY, UNIVERSITY OF MICHIGAN: INSTRUCTOR TO ASSOCIATE PROFESSOR, DEPARTMENTS OF PSYCHOLOGY AND OPHTHALMOLOGY; DIRECTOR, VISION RESEARCH LABORATORY; SUPERVISOR, INSTITUTE FOR INDUSTIAL HEALTH; SUPERVISOR, ENGINEERING RESEARCH INSTITUTE.
1958-	MEMBER OF FACULTY, OHIO STATE UNIVERSITY; PROFESSOR AND DIRECTOR, INSTITUTE FOR RESEARCH IN VISION; PROFESSOR PHYSIOLOGICAL OPTICS IN OPTOMETRY; RESEARCH PROFESSOR IN OPHTHALMOLOGY.
1945-55	OFFICIAL OF THE ARMED FORCES NATIONAL RESEARCH COUNCIL VISION COMMITTEE; TECHNICAL AIDE TO EXECUTIVE SECRETARY.

HONORS:

	MEMBER PHI BETA KAPPA; 15 YEAR HONOR MAN OF HAVERFORD COLLEGE CHAPTER MEMBER, SIGMA XI.
1947	ARMY-NAVY CERTIFICATION OF APPRECIATION FOR WORLD WAS II RESEARCH.
1950	ADOLPH LOMB MEDAL OF THE OPTICAL SOCIETY OF AMERICA.
1958	CITATION FOR MEDICAL AUTHORSHIP, INDUSTRIAL MEDICAL ASSOCIATION.
1960	CERTIFICATE OF DISTINGUISHED SERVICE, ILLUMINATING ENGINEERING RESEARCH INSTITUTE.

PERSONAL ACTIVITIES:

FELLOW, OPTICAL SOCIETY OF AMERICA.
FELLOW, ILLUMINATING ENGINEERING SOCIETY.
FELLOW, AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE.
FELLOW, AMERICAN ACADEMY OF OPTOMETRY.
MEMBER, AMERICAN PHYCHOLOGICAL ASSOCIATION.
MEMBER, NIGHT VISIBILITY COMMITTEE HIGHWAY RESEARCH BOARD.
PRESIDENT, EXPERT COMMITTEE ON VISUAL PERFORMANCE, INTERNATIONAL COMMISSION ON ILLUMINATION.
NATIONAL RESEARCH COUNCIL MEMBER, ARMED FORCES NATIONAL RESEARCH COUNCIL COMMITTEE ON VISION.
ADVISOR, NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM.
ADVISOR, ILLUMINATING ENGINEERING RESEARCH INSTITUTE.

THOSE IN ATTENDANCE:

THE SPEAKER AND MRS. H. RICHARD (OLIVE) BLACKWELL

ADMINISTRATIVE STAFF OF THE DADE COUNTY BOARD OF PUBLIC INSTRUCTION -

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MR. HAROLD SECKINGER, REPRESENTING THOMAS MADDEN, ARCHITECT

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- MR. HARVEY PIERCE, CONNELL, PIERCE, GARLAND & FRIEDMAN
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- MR. LEONARD HAYET, SMITH, KORACH & ARNOLD
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- MR. ROBERT WHITWORTH, R.L. DUFFER ASSOCIATES
- MR. RALPH SELLS, BROWN-SELLS & ASSOCIATES

REPRESENTATIVES OF PANCOAST, FERENDINO, GRAFTON & SKEELS, ARCHITECTS AND ENGINEERS, ARCHITECTS TO THE DADE COUNTY BOARD OF PUBLIC INSTRUCTION -

- MR. RUSSELL T. PANCOAST, FA.I.A.
- MR. ANDREW J. FERENDINO, A.I.A.
- MR. EDWARD G. GRAFTON, A.I.A.
- MR. NORMAN A. SKEELS, A.I.A.
- MR. LESTER C. PANCOAST, A.I.A.
- MR. W. PINSON WHIDDON, A.I.A.
- MR. HILARIO CANDELA
- MR. JAMES H. CHURCH, A.I.A.
- MR. LOUIS LAMPERTY, P.E.
- MR. EDWIN JONES, P.E.

SESSION OF SEMINAR ON THE PRESENT STATUS OF VISION ENGINEERING

CEILING OF EXECUTIVE SUITE OF PANCOAST/FERENDINO/GRAFTON/ARCHITECTS IS FORMED BY LAY-IN POLARIZED LIGHTING PANELS.

THE FOLLOWING IS AN ATTEMPT TO PARAPHRASE FORTY-FIVE MINUTES OF DISCUSSION BY DR. BLACKWELL, AND ONE HOUR AND FIFTEEN MINUTES OF QUESTIONS AND ANSWERS.

THE HARDEST QUESTION TO ANSWER ABOUT LIGHTING IS HOW MUCH IS REQUIRED. ONE REASON IS THAT THE REQUIREMENT VARIES SO MUCH WITH THE DIFFICULTY OF THE TASK TO BE PERFORMED. FOR EXAMPLE, BOLD PRINT CAN BE READ WITH 1 TO 10 FOOT-CANDLES , AND MORE DIFFICULT TASKS REQUIRE INCREASING QUANTITIES OF LIGHT. HOWEVER, AT THE OTHER END OF THE SCALE FEW THINGS ARE SO DIFFICULT AS TO REQUIRE MORE THAN 150 FOOTCANDLES. IF THE SUBJECT IS ABLE TO DISCERN MORE DETAIL IT MAKES SEEING EASIER. RESEARCH INDICATES THAT FOR THE ABILITY TO SEE IN DETAIL, DISTRIBUTION OR UNIFORMITY IS MORE IMPORTANT THAN QUANTITY TO ACHIEVE WHAT WE MAY TERM QUALITY IN LIGHTING. THE MARVELOUS ABILITY OF THE EYE TO ADAPT THE VARYING LEVELS AND QUALITY OF LIGHT MAKES AN ANSWER TO THE FIRST QUESTION IMPOSSIBLE WITHOUT FEAR OF CONTRADICTION IN THE FUTURE WHEN NEW FACTS ARE LEARNED. THE PUBLISHED STANDARDS ARE BASED ON THE ASSUMPTION THAT THE QUALITY OF LIGHTING IS GOOD FOR RECOMMENDED FOOTCANDLE LEVELS. WE KNOW THAT ACTUAL FIELD CONDITIONS FALL SHORT OF LABORATORY CONDITIONS UNDER WHICH THE RECOMMENDED LEVELS WERE ARRIVED AT FOR VARIOUS TASKS.

IF SEEING IS POSSIBLE UNDER A WIDE RANGE OF LIGHTING CONDITIONS, SUCH AS ABE LINCOLN READING BEFORE A FIREPLACE, WE MAY ASK WHAT IS THE IMPORTANCE OF MAKING IT EASY TO SEE. THE ANSWER IS FOUND IN LARGE NUMBER OF ADJUSTMENTS THAT MUST BE MADE BY THE MUSCLES OF THE EYE IN DIRECTING, FOCUSING, AND CON-TRACTING OR DILATING THE PUPIL TO ADJUST TO INTENSITY OF LIGHT. TO TRIGGER THESE COMPLICATED REACTIONS REQUIRES A REASONABLE SIGNAL OR STIMULUS. WHEN THIS IS NOT PRESENT MORE EFFORT MUST BE EXPENDED TO COMPENSATE, AND WHILE WE MAY NOT BE CONSCIOUS OF THIS AT THE TIME, THE RESULT MAY OFTEN BE THAT THE MUSCLES ACHE IN A DELAYED REACTION. ANOTHER CONSEQUENCE MAY BE THE FORMING OF BAD HABITS IN READING. FAILING TO RECEIVE STRONG ENOUGH SIGNAL TO PERCEIVE, THE EYE MUST BACKTRACK TO VERIFY THE INFORMATION, SLOWING UP THE PROCESS AND SPOILING SPEED OF PERFORMANCE. THIS IS DIFFICULT TO OVERCOME LATER EVEN IN THE PRESENCE OF IMPROVED CONDITIONS. THIS TENDENCY IS MOST CRITICAL IN SCHOOLS WHERE OUR HABITS ARE FORMED AT MANY TASKS.

THE DELAYED REACTION IS CHARACTERISTIC OF INADEQUATE QUANTITY OR REFLECTED GLARE MASKING CONTRAST BELOW AN ACCEPTABLE LEVEL FOR A SEEING TASK. IN THE CASE OF DIRECT GLARE THE EFFECT ON AND DISCOMFORT OF THE SUBJECT IS IMMEDIATE. BY DIRECT GLARE WE MEAN THE RAYS OF LIGHT WHICH REACH THE EYE WITHOUT REFLECTION DIRECTLY FROM THE SOURCE (EITHER ARTIFICAL LUMINAIRE OR NATURAL DAYLIGHT). BECAUSE IT IS IMMEDIATELY OBVIOUS, CORRECTION FOR DIRECT GLARE HAS GENERALLY BEEN MADE BY SHIELDING OR DIFFUSION OF ARTIFICIAL LIGHTS, AND WITH BLINDS OR SUNSHADES FOR WINDOWS OR SKYLIGHTS. THE NEED FOR ADEQUATE LEVELS AND THE ELIMINATION OF VEILING REFLECTED GLARE TO AVOID DELAYED REACTION IS LESS OBVIOUS AND THEREFORE SLOWER TO BE ACCOMPLISHED IN PRACTICE. GREAT STRIDES HAVE BEEN MADE RECENTLY IN BOOSTING RECOMMENDED LEVELS, BUT MORE RECENT RESEARCH ESTABLISHES THE NEED TO CONSIDER THE QUALITY OF LIGHT FURNISHED AS WELL AS THE QUANTITY.

SINCE THE AMOUNT OF LIGHT REQUIRED DEPENDS ON THE TASK TO BE PERFORMED RATHER THAN WHERE YOU ARE WHILE PERFORMING IT, WHETHER SCHOOL, OFFICE OR HOME, YOU CANNOT AFFORD TO BE DOGMATIC ABOUT QUANTITY. AFTER ALL, THE TASKS MAY CHANGE IN A GIVEN AREA. THE EVIDENCE POINTS TO THE FACT THAT QUALITY MAY PROVE MORE IMPORTANT THAN QUANTITY IN WHAT CONSTITUTES A GOOD LIGHTING SYSTEM. THIS IS BECAUSE IT TAKES MORE INCREASE IN INTENSITY TO PROVIDE THE CONTRAST NECESSARY FOR SEEING A GIVEN TASK IN THE PRESENCE OF REFLECTED GLARE THAN COULD BE PURCHASED FOR THE SAME DOLLAR VALUE INVESTED IN GLARE REDUCING EQUIPMENT.

THE NATURE OF LIGHT FURNISHED FOR PERFORMING TASKS VARIES WIDELY FROM THE THEORETICAL EQUAL IN ALL DIRECTIONS PRODUCED IN THE LABORATORY TEST SPHERE, WHICH IS IN PRACTICE MOST NEARLY ACHIEVED IN WELL BALANCED INDIRECT LIGHT SYSTEMS, TO OTHER EXTREME WHICH IS THE SHAPED CURVE OF THE COMMERCIAL DIRECT LIGHTING FIXTURE. BECAUSE THE LIGHT REACHING THE TASK IS FROM ALL DIRECTIONS THERE CAN BE NO UNFOCUSED REFLECTED IMMAGE OF THE SOURCE WHICH WE CALL GLARE UNDER INDIRECT LIGHT. SUCH A SYSTEM IS SO WASTEFUL OF ENERGY BECAUSE SO LITTLE OF THE TOTAL LIGHT IS DIRECTED ON THE TASK THAT THE COST IS PROHIBITIVE.

THE AIM OF DESIGN SHOULD BE TO PRODUCE AS NEAR AS POSSIBLE THE EFFECT OF INDIRECT LIGHT WITHOUT THE EXCESSIVE COST FOR LIGHTING ENERGY AND THE NECESSITY FOR REMOVING ADDITIONAL HEAT IN AIR CONDITIONED STRUCTURES. TESTS CONDUCTED ON PERFECT DIFFUSED PANELS, GLASS OR PLASTIC LENSES, AND MULTILAYER POLARIZER INDICATE THAT THE BEST QUALITY OF LIGHTING IS PRODUCED BY A LUMINOUS CEILING OF MULTILAYER POLARIZER PANELS AND THE WORST WAS STRIPS OF DIFFUSED PANELS. IN ORDER TO PRODUCE ADEQUATE LIGHT LEVEL FOR THE TASK UNDER CONSIDERATION THE PERFECT DIFFUSER REQUIRED BRIGHTNESS OF THE SOURCE THAT PRODUCED EXCESSIVE DIRECT GLARE. A STRIP LIGHTING INSTALLATION CAN REQUIRE TWO OR THREE TIMES AS MANY FOOTCANDLES FOR THE SAME TASK BECAUSE OF THE GEOMETRY OF THE LIGHT RAYS FORMING AN UNFOCUSED IMAGE TO CREATE VEILING REFLECTED GLARE.

THE GLASS OR PLASTIC LENS OVERCOMES THE DISADVANTAGE OF THE DIFFUSED PANEL INSOFAR AS DIRECT GLARE IS CONCERNED BY CUTTING OFF HORIZONTAL RAYS AND DIRECTING THE LIGHT DOWNWARD TO THE WORKING PLANE. THIS CUT-OFF IS GOOD AND MOST EFFECTIVE FOR THE FIXTURES OR PANELS ACROSS THE ROOM AND HENCE NEAREST TO THE HORIZON OR LINE OF VISION OF THE WORKER OR STUDENT. THE DISADVANTAGE IS THAT THIS SAME LIGHT DIRECTED DOWNWARD CREATES THE MOST REFLECTED GLARE DUE TO THE FACT THAT THE ANGLE OF INCIDENCE COINCIDES WITH THE VIEWING ANGLE OF A MOJORITY OF TASKS.

THE MULTILAYER POLARIZER PANEL HAS THE SAME ADVANTAGE AS THE GLASS OR PLASTIC LENS IN THAT IT HAS THE SAME PROPERTY OF CUT-OFF TO REDUCE THE DIRECT GLARE. IN FACT, THE PANELS ACROSS THE ROOM WILL APPEAR GREY BECAUSE SO MUCH OF THE HORIZONTAL WAVE LENGTHS ARE REFLECTED BACK. BECAUSE POLARIZATION IS ACHIEVED BY REFLECTION RATHER THAN ABSORPTION THE HORIZONTALLY PLANE POLARIZED LIGHT IS NOT LOST AND CAN BE DE-POLARIZED BY A SUITABLE BACK PLATE AND REFLECTED FOR ANOTHER AND YET ANOTHER CHANCE TO PASS THROUGH THE MULTILAYER SHEET. LIGHT

TRANSMITTED IS PREFERENTIALLY VERTICALLY PLANE POLARIZED BECAUSE LIGHT REFLECTED FROM A FLAT SURFACE IS HORIZONTALLY PLANE POLARIZED. THE SELECTIVE EFFECT IS MAGNIFIED BY PILING UP REFLECTING SURFACES UNTIL NEARLY PURE VERTICALLY PLANE POLARIZED LIGHT IS ACHIEVED.

BECAUSE LIGHT REFLECTED DIRECTLY FROM SOLID FLAT SURFACES TENDS TO BE PREDOMINATELY HORIZONTALLY PLANE POLARIZED IF BY THE USE OF MULTILAYER POLARIZER PANELS AT THE LIGHT SOURCE WE REMOVE MOST OF THE HORIZONTALLY POLARIZED LIGHT, THE RESULTING VERTICALLY PLANE POLARIZED LIGHT WILL BE ABSORBED AND THEN REFLECTED AS UNPOLARIZED LIGHT REVEALING TO THE EYE THE CONTRAST, COLOR AND TEXTURE OF THE TASK WITHOUT THE VEILING GLARE OF DIRECT REFLECTED LIGHT PRESENT WITHOUT POLARIZATION.

THE QUESTION WAS ASKED: "HOW ABOUT THE ROOM IN WHICH THE RECOMMENDED LIGHT SOURCE IS INSTALLED?" TO THIS DR. BLACKWELL REPLIED THAT "FIRST, THE BIGGER THE BETTER SINCE THIS TENDS TO IMPROVE THE GEOMETRY OF THE SOURCE OF THE RAYS OF LIGHT. SECOND, REFLECTANCES THAT ARE HIGHER ARE BETTER, THE SAME AS FOR OTHER LIGHTING SYSTEMS. THE RANGES RECOMMENDED BY AMERICAN STANDARDS ASSOCIATION A23.1 SHOULD BE ADHERED TO WHERE POSSIBLE." WHILE THE LAYOUT OF LAMPS MAY BE VARIABLE WITH LESS PENALTY FOR REDUCTION THAN WITH OTHER SYSTEMS, THIS INFLUENCES RESULTS THE MOST IN TERMS OF SEEING THE TASK. LIKE ANY CLASS OF USEFUL PRODUCTS, MULTILAYER POLARIZERS MAY BE MADE WITH HIGH OR LOW EFFECTIVENESS. THEY SHOULD BE CERTIFIED WITH RESPECT TO THE VISUAL EFFECTIVENESS FACTORS (VEF) AND INDEX OF COMFORTABLE ILLUMINATION (ICI), AS WELL AS WITH RESPECT TO THEIR EFFECTIVENESS IN PROVIDING ILLUMINATION FROM LAMP LUMENS.

FROM THE STANDPOINT OF SEEING A GIVEN TASK BRIGHTNESS BALANCE IN A ROOM IS OF HIGH PRIORITY. EXTREMES LIKE THE DARK BLACKBOARDS AND THE NATURAL LIGHT FROM A WINDOW THROW A MONKEY WRENCH IN THE MECHANISM OF THE EYE. YOU ARE NATURALLY DRAWN TO CONTRAST, AND THE EYE MUSCLES MUST READAPT DIRECTION, IRIS OPENING AND FOCUS WHEN YOU RETURN TO THE TASK. WHILE CONTRAST IS ESSENTIAL TO BLACKBOARD VIEWING, AND WHITE CHALK IS THE BEST TO PROVIDE THIS, COLORED CHALKBOARDS ARE A SENSIBLE COMPROMISE FOR HIGHER REFLECTANCE. IT WAS SUGGESTED FROM THE FLOOR THAT MINERAL IMPREGNATED FLUORESCENT CHALK BE USED TO IMPROVE CONTRAST. IN THE SPEAKER'S OPINION SUPPLEMENTAL LIGHTING SHOULD BE PROVIDED AT CHALKBOARDS ALTHOUGH FEW, IF ANY, STOCK FIXTURES ARE OFFERED FOR THIS APPLICATION. WINDOWS, PARTICULARLY AT EYE LEVEL, FOR VIEWING SHOULD BE GLAZED WITH GLARE REDUCING GLASS.

THE WHITE-OUT WHICH OCCURS IN THE ARCTIC ILLUSTRATES THE EXTREME AS REGARDS THE HIGH REFLECTANCE OF ENVIRONMENT IN WHICH THE SUBJECT MAY LOSE SENSE OF DIRECTION. THIS IS HARDLY LIKELY WITH NORMAL MATERIALS, AND VARIETY AND ORIENTATION CAN BE ACHIEVED BY COLOR AND TEXTURE WHICH CAN VARY WITH EQUAL BRIGHTNESS.

TO THE QUESTION WHETHER THE INTRODUCTION OF DAYLIGHT AFFECTED THE CHOICE OF LIGHTING SYSTEMS, THE REPLY WAS THAT IT REDUCES THE DIFFERENCES BUT NOT THE ORDER OF EXCELLENCE.

RETURNING TO THE ORIGINAL QUESTION OF QUANTITY THE FACT REMAINS THAT THE EYE CAN SEE WITH LESS CONTRAST IN THE TASK WITH A GREATER QUANTITY. WHAT THE BRITISH CALL "THE AMENITY OF LIGHTING" CALLS FOR MORE. GIVEN A DIMMER SWITCH TO CONTROL THEIR OWN ENVIRONMENT MOST SUBJECTS WILL INCREASE THE LEVEL TO THE MAXIMUM WHEN REQUESTED TO ADJUST TO THEIR PREFERENCE.

REGARDING COLOR RENDITION IT WAS ADMITTED THAT FLUORESCENT SOURCES DISTORT COLOR MORE, HOWEVER, THEY HAVE BEEN IMPROVED OVER CERTAIN SPECTRAL AREAS SINCE THEIR INTRODUCTION. IN THIS RESPECT POLARIZED LIGHT IMPROVES COLOR RENDITION BY THE REMOVAL OF THE COLOR OF THE LIGHT SOURCE PRESENT IN REFLECTED GLARE. THE RESULT IS A SATURATION IMPROVEMENT WITH EQUAL REFLECTANCE UNDER VERTICALLY POLARIZED LIGHT. MATERIALS WITH BEAUTY IN THEIR DEPTH LIKE WOOD GRAIN SHOW BETTER UNDER POLARIZED LIGHT.

WHILE IT MAY HAVE VERY DEFINITE PSYCHOLOGICAL EFFECTS ON THE VIEWER, COLOR IS NOT THE FACTOR THAT REFLECTANCE AND CONTRAST ARE, IN SEEING A GIVEN TASK. THERE IS A LITTLE LESS GLARE PRESENT WITH WARM THAN WITH COOL COLOR.

THE DISCUSSION AND QUESTION PERIOD PROVED SO STIMULATING THAT MANY REMAINED FOR AN ADDITIONAL HOUR AND A HALF DISCUSSING THE SUBJECT OF LIGHTING IN GENERAL AND THE VIRTUES OF POLARIZED LIGHTING IN PARTICULAR SUCH AS THAT IN THE ROOM IN WHICH THE MEETING WAS HELD.

THE FOLLOWING IS THE PAPER PRESENTED THE NEXT DAY, SEPTEMBER 1, AT THE CONVENTION OF THE ILLUMINATING ENGINEERING SOCIETY ON MIAMI BEACH AND DESCRIBES THE MOST RECENT RESEARCH AND CONCLUSIONS REFERRED TO BY DR. BLACKWELL IN HIS TALK TO THE GROUP ASSEMBLED AT THE OFFICES OF PANCOAST, FERENDINO, GRAFTON AND SKEELS.

I. INTRODUCTION

THE DESIGN AND EVALUATION OF LIGHTING HAS TRADITIONALLY FALLEN WITHIN THE PROVINCE OF THE ILLUMINATION SUB-SPECIALTY OF ELECTRICAL ENGINEERING. HOWEVER, IT HAS BECOME INCREASINGLY APPARENT IN RECENT YEARS THAT MANY OF THE MOST DIFFICULT PROBLEMS IN THE LIGHTING FIELD DEPEND FOR THEIR SOLUTION UPON FACTS CONCERNING THE PHYSIOLOGY AND PSYCHOLOGY OF THE HUMAN USER OF LIGHT. THE SCIENTIFIC STUDY OF HUMAN VISION HAS BEEN GREATLY ADVANCED IN RECENT YEARS, AND IT NOW SEEMS REASONABLE TO SPEAK OF VISUAL SCIENCE. IT ALSO SEEMS USEFUL TO REFER TO VISION ENGINEERING AS THE TECHNOLOGY OF APPLICATION OF OUR KNOWLEDGE OF VISUAL SCIENCE TO CERTAIN PROBLEMS IN THE FIELD OF LIGHTING. VISION ENGINEERING IS CONCERNED WITH SUCH PROBLEMS AS THE ESTABLISHMENT OF STANDARDS OF QUANTITY OF ILLUMINATION FOR DIFFERENT VISUAL ACTIVITIES, AND THE EVALUATION OF THE RELATIVE EFFECTIVENESS OF DIFFERENT TYPES OF LIGHTING INSTALLATION IN SUPPLYING VISUAL NEEDS. THE PROBLEMS OF PROVIDING THE NEEDED LEVELS OF VISUALLY EFFECTIVE ILLUMINATION BY EFFICIENT TECHNICAL MEANS REMAINS THE PROVINCE OF ILLUMINATING ENGINEERING. THIS DISTINCTION IS NOT OF FUNDAMENTAL SIGNIFICANCE, BUT IT DOES TEND TO PLACE EMPHASIS UPON THE KINDS OF SCIENTIFIC INFORMATION REQUIRED TO SOLVE DIFFERENT CLASSES OF TECHNICAL PROBLEMS ENCOUNTERED IN THE FIELD OF LIGHTING.

I WOULD LIKE TO DEMONSTRATE THE GENERAL METHOD AND CONTENT OF VISION ENGINEERING BY DESCRIBING THE PRESENT STATUS OF MY METHODS FOR ESTABLISHING THE ILLUMINATION LEVELS NEEDED FOR VARIOUS VISUAL ACTIVITIES AND FOR EVALUATING THE VISUAL EFFECTIVENESS OF VARIOUS TYPES OF LIGHTING INSTALLATIONS. BEFORE DOING SO, HOWEVER, I WOULD LIKE TO MAKE A FEW GENERAL REMARKS ABOUT THE EFFECTS OF LIGHT UPON SIGHT.

II. BROAD ASPECTS OF THE EFFECT OF LIGHT UPON SIGHT

THE PHYSICAL CHARACTERISTICS OF ILLUMINATION WHICH AFFECT VISION INCLUDE THE AMOUNT OF INTENSITY OF LIGHT, THE DIRECTION AT WHICH LIGHT RAYS STRIKE OBJECTS TO BE SEEN, THE PLANE POLARIZATION, AND THE COLOR OF LIGHT. THE PATTERN OF LUMINANCES OR BRIGHTNESSES OF THE ENTIRE ENVIRONMENT IS ALSO OF INTEREST, AND THIS DEPENDS UPON THE PHYSICAL CHARACTERISTICS OF THE LIGHTING SYSTEM AND THE REFLECTANCE CHARACTERISTICS OF OBJECTS IN THE ENVIRONMENT. LIGHTING IS OFTEN DESCRIBED IN TERMS OF QUANTITY (INTENSITY), AND QUALITY, WHERE THE LATTER TERM IS USED TO REFER TO ALL ASPECTS OF ILLUMINATION AND BRIGHTNESS OTHER THAN QUANTITY. BOTH QUANTITY AND QUALITY OF LIGHT MUST BE EVALUATED IN TERMS OF THEIR EFFECT UPON VISION. WHEREAS A USER OF LIGHT MAY BE SOMEWHAT AWARE OF SOME ASPECTS OF THE EFFECT OF LIGHT UPON SIGHT, SCIENTIFIC EVIDENCE IS OUR BEST GUIDE IN EVALUATING ALL ASPECTS OF LIGHTING SYSTEMS. LIGHTING CAN BE GOOD OR BAD WITH RESPECT EITHER TO QUANTITY AND QUALITY OR BOTH.

SEEING IS A COMPLEX ORGANIC BEHAVIOR INVOLVING A NUMBER OF BRAIN CENTERS IN ADDITION TO THE EYE. THE EYE RECEIVES LIGHT STIMULI WHICH ARE PROCESSED WITHIN THE EYE AND IN HIGHER BRAIN CENTERS TO PROVIDE INFORMATION. SOME OF THIS INFORMATION IS USED IMMEDIATELY TO GUIDE THE BEHAVIOR OF THE ORGANISM; MOST OF THE INFORMATION IS STORED AS KNOWLEDGE. AN ESPECIALLY IMPORTANT CLASS OF INFORMATION FOR OUR PURPOSES IN EVALUATING LIGHTING IS THAT WHICH IS USED TO PROGRAM THE ADJUSTMENTS OF THE EYES WHICH AID IN THE COLLECTION OF FURTHER INFORMATION. WHAT WE SEE GUIDES THE ADJUSTMENT OF MUSCLES IN THE EYE WHOSE ADJUSTMENTS THEN AFFECT WHAT WE NEXT SEE. I REFER TO THE MUSCLES WHICH OPERATE THE IRIS OF THE EYE, THOSE WHICH ALTER THE EYES' FOCUS, AND THOSE WHICH DIRECT THE EYES TOWARD ONE OR ANOTHER POINT IN THE SPACE ABOUT US. THE SERVO-LOUP INVOLVED IN "SIMPLE" SEEING HAS ALMOST INCREDIBLE PRECISION IN PROGRAMMING THE SEQUENCE OF LOOKING, SEEING AND LOOKING. THE PROCESSING OF INFORMATION BY THE BRAIN SEEMS TO FOLLOW THE PROGRAM WHICH IS ITSELF LARGELY DICTATED BY THE ESTABLISHED SEQUENCE OF EYE MOVEMENTS AND INFORMATION COLLECTION.

SO FAR AS WE KNOW, THE EYEBALL IS NOT STRUCTURALLY DAMAGED BY BAD LIGHTING, EITHER INSUFFICIENT QUANTITY OR POOR QUALITY. IT IS EASY TO SHOW THAT THE EFFECTIVENESS OF INFORMATION COLLECTION IS REDUCED IN BAD LIGHT. THERE IS SOME REASON TO BELIEVE THAT SEEING UNDER BAD LIGHT CAN LEAD TO THE DEVELOPMENT OF INEFFECTIVE PROGRAMMING OF THE INFORMATION-COLLECTION PROCESS WHICH MAY BECOME HABITUAL. HOWEVER, WE DO NOT HAVE CLEAR SCIENTIFIC EVIDENCE ON THIS IMPORTANT POINT. THE EFFECTIVENESS WITH WHICH A HUMAN LEARNS WHILE SEEING IS SIMPLY SUCH A COMPLEX AFFAIR THAT WE HAVE NOT FOUND A SATISFACTORY METHOD FOR STUDYING IT UNDER DIFFERENT LIGHTING CONDITIONS.

WE ALSO NOW KNOW THAT BAD LIGHTING WHICH REDUCES THE EFFECTIVENESS OF INFORMATION COLLECTION CAN LEAD TO LOCALIZED OR GENERAL DISCOMFORT. SOME OF THE DISCOMFORT APPARENTLY CAN BE TRACED TO LIGHTING CONDITIONS WHICH OVER-STIMULATE SOME OF THE EYE ADJUSTMENT PROCESSES, AS IN THE CASE OF REPEATED CONSTRICTIONS AND RELAXATIONS OF THE IRIS. MORE OF THE DISCOMFORT APPARENTLY CAN BE TRACED TO LIGHTING CONDITIONS WHICH LEAD TO A REDUCTION IN INFORMATION NEEDED TO GUIDE THE EYE ADJUSTMENT PROCESSES. THUS, BAD LIGHTING INTERFERES WITH THE SENSORY STIMULI NEEDED TO CONTROL BOTH EYE FOCUS AND EYE POINTING. POORLY PROGRAMMED FOCUS AND POINTING ADJUSTMENTS PRODUCE DISCOMFORT WHICH DEVELOPS SLOWLY, AND INDEED WHICH MAY BE DELAYED UNTIL AFTER THE OFFENDING USE OF THE EYES HAS BEEN TERMINATED. THESE EFFECTS OF LIGHTING REQUIRE FURTHER STUDY BUT, UNFORTUNATELY, THE STUDY OF DISCOMFORT DUE TO POOR PROGRAMMING OF EYE ADJUSTMENT FUNCTIONS HAS PROVED COMPARATIVELY DIFFICULT.

WE HAVE CLEAR AND COMPREHENSIVE DATA IN TWO AREAS. FIRST, WE CAN RELATE THE DEGREE OF VISIBILITY OF VISUAL TASKS TO LIGHTING VARIABLES WITH A GREAT DEAL OF PRECISION. VISIBILITY IS OBVIOUSLY IMPORTANT BECAUSE WE CANNOT BE INFLUENCED BY WHAT WE CANNOT SEE IN THE ENVIRONMENT AROUND US. AS IMPORTANT AS THIS IS, IT MAY BE AT LEAST AS IMPORTANT THAT POOR VISIBILITY LEADS TO POOR

EYE ADJUSTMENTS WHICH LEAD TO DISCOMFORT AND WHICH MAY LEAD TO HARMFUL HABITS OF INFORMATION-COLLECTION. SECONDLY, WE CAN DESCRIBE THE DEGREES OF DISCOMFORT PRODUCED IMMEDIATELY IN A LIGHTED ENVIRONMENT BY WHAT IS CALLED DIRECT GLARE. LET ME PRESENT RECENT FINDINGS IN THESE TWO AREAS, AND THEN USE THEM AS A BASIS FOR EVALUATING LIGHTING NEEDS AND THE EFFECTIVENESS OF DIFFERENT LIGHTING INSTALLATIONS.

III. LIGHTING VARIABLES AND TASK VISIBILITY

MY STUDIES REPORTED IN 1959 (REF. 1) DETERMINED THE DEGREE TO WHICH DIFFERENT VISUAL TASKS REQUIRE DIFFERENT LEVELS OF ILLUMINATION INTENSITY FOR EQUAL VISIBILITY. FIRST, TEST SUBJECTS WERE REQUIRED TO IDENTIFY CORRECTLY WHEN WE PRESENTED A SMALL (4 MINUTE) DISC OF LIGHT IN A LARGE FIELD OF UNIFORM BRIGHTNESS. THE SUBJECTS HAD TO DETECT THE PRESENCE OF THE DISC IN 1/5 SECOND, SINCE THIS IS THE LENGTH OF TIME THE EYE NORMALLY PAUSES TO FIXATE. WE VARIED THE PHYSICAL CONTRAST OF THE DISC TO VARY ITS DIFFICULTY, AND DETERMINED ILLUMINATION LEVELS WHICH WERE NEEDED TO BRING TASKS OF DIFFERING DIFFICULTY TO EQUAL VISIBILITY. THE SUBJECTS WERE ABLE TO ADJUST THEIR EYES FULLY BEFORE THE DISC WAS PRESENTED, AND HAD NO NEED TO SEARCH AND SCAN. THEY WERE ALSO SPECIFICALLY WELL-TRAINED IN DETECTING THE PRESENCE OF THE DISCS. OTHER EXPERIMENTS SUGGESTED THAT A FIELD FACTOR OF 15 WOULD PROVIDE MOST USERS OF LIGHT WITH A REASONABLE LEVEL OF TASK VISIBILITY UNDER THE MORE DIFFICULT CONDITIONS OF ORDINARY SEEING. DATA REPRESENTING A FIELD FACTOR OF 15 WERE USED TO DEFINE A "STANDARD PERFORMANCE" CURVE WHICH HAS BEEN USED BY OUR ILLUMINATING ENGINEERING SOCIETY TO DEFINE THE LEVEL OF VISUAL PERFORMANCE TO BE PROVIDED BY ILLUMINATION.

THE METHOD OF SPECIFYING ILLUMINATION LEVELS FOR DIFFERENT TASKS OF INTEREST MAY BE DESCRIBED AS FOLLOWS: REAL VISUAL TASKS VARY IN THEIR INTRINSIC DIFFICULTY DUE TO THEIR SIZE, THE DISTANCE AT WHICH THEY ARE VIEWED, THEIR PHYSICAL CONTRAST, THEIR COLOR WITH RESPECT TO THEIR BACKGROUND AND SO ON. WE RATE THE DIFFICULTY OF A TASK IN TERMS OF THE PHYSICAL CONTRAST REQUIRED TO MAKE OUR STANDARD 4-MINUTE DISC EQUALLY DIFFICULT WHEN VIEWED UNDER THE SAME CONDITIONS. THE EQUATION OF DIFFICULTY OF A REAL TASK TO THE STANDARD TASK IS MADE WITH AN OPTICAL DEVICE KNOWN AS THE VISUAL TASK EVALUATOR. THE DIFFICULTY OF A TASK OF INTEREST IS DESIGNATED BY $\tilde{C}$, THE EQUIVALENT CONTRAST OF THE DISC OF EQUAL DIFFICULTY. THE REQUIRED QUANTITY OF ILLUMINATION, $E_{\underset{\sim}{R}}$, FOR THE TASK IS READ FROM THE STANDARD PERFORMANCE CURVE AT THE VALUE OF $\tilde{C}$. IN EFFECT, IT IS ASSUMED THAT THE TASKS EQUAL IN DIFFICULTY REQUIRE EQUAL LEVELS OF ILLUMINATION TO SATISFY THE STANDARD VISUAL PERFORMANCE CRITERION. IT IS WORTH EMPHASIZING THAT THE ABSOLUTE LEVELS OF ILLUMINATION GIVEN BY THE STANDARD PERFORMANCE CURVE DEPEND UPON THE ASSUMPTION WE MADE WITH REGARD TO THE DESIRABLE LEVEL OF TASK VISIBILITY TO BE PROVIDED BY ILLUMINATION, AND HENCE ARE TO SOME EXTENT AT LEAST ARBITRARY. WE CAN BE MUCH MORE POSITIVE, HOWEVER, ABOUT THE <u>RELATIVE AMOUNTS OF LIGHT NEEDED FOR DIFFERENT TASKS</u>. THESE DO NOT DEPEND UPON THE ASSUMED LEVEL OF DESIRABLE TASK VISIBILITY, BUT DEPEND ONLY UPON THE BASIC

FORM OF THE PERFORMANCE CURVE WHICH IS A FUNDAMENTAL PROPERTY OF THE HUMAN VISUAL SYSTEM.

THE REQUIRED FOOTCANDLES OBTAINED IN THIS MANNER FOR SOME TASKS WHICH OCCUR FREQUENTLY IN INTERIOR ENVIRONMENTS HAVE BEEN SUMMARIZED IN TABLE I. NOTE THAT READING LARGE BLACK PRINT REQUIRES ONLY ABOUT 1 FOOTCANDLE, WHEREAS FINDING A BROKEN WHITE THREAD REQUIRES MORE THAN 400 FOOTCANDLES. WE MUST CONCLUDE THAT THE LIGHT INTENSITY WE REQUIRE DEPENDS DRASTICALLY UPON THE TASK WE ARE TO PERFORM. THIS CONCLUSION PERHAPS SUGGESTS THE USE OF LOCALIZED LIGHTING FOR AREAS WHERE THE MOST DIFFICULT TASKS ARE PERFORMED. THE SELECTION OF AN ILLUMINATION LEVEL TO BE USED IN AN ENVIRONMENT OBVIOUSLY DEPENDS UPON OUR HAVING KNOWLEDGE OF THE IMPORTANT TASKS WHICH WILL BE PERFORMED FREQUENTLY IN THAT ENVIRONMENT. THE TASK OF READING WELL-PRINTED BOOKS HAPPENS TO BE AN UNUSUALLY EASY ONE AND IS NOT SUITABLE TO USE AS A STANDARD TASK UNLESS TASKS OF GREATER DIFFICULTY ARE SELDOM PERFORMED.

THE FOOTCANDLE REQUIREMENTS CONTAINED IN TABLE I ALL REPRESENT WHAT HAS BEEN CALLED "GLARE-FREE" LIGHT. MY WORK SINCE 1959 HAS MADE IT ABUNDANTLY CLEAR (REF. 2) THAT THE PHYSICAL PROPORTION OF LIGHTING INSTALLATIONS INFLUENCE THE DIFFICULTY OF VISUAL TASKS DUE TO THE MICROSCOPIC OPTICAL PROPERTIES OF THE TASKS. FOR EXAMPLE, A LIGHT RAY COMING FROM ONE POINT IN SPACE MAY PRODUCE A LARGE TASK CONTRAST, WHEREAS A RAY COMING FROM ANOTHER POINT IN SPACE MAY TEND TO WASH-OUT TASK CONTRAST AND REDUCE TASK VISIBILITY. WHEN THE WASH-OUT OF TASK CONTRAST IS VERY NOTICEABLE, THE LIGHTING SYSTEM IS SAID TO PRODUCE "REFLECTED GLARE". HOWEVER, THE DEGREE OF TASK CONTRAST ALWAYS DEPENDS UPON THE PHYSICAL PROPERTIES OF THE TASK AND LIGHTING INSTALLATION WHETHER OR NOT "REFLECTED GLARE" IS VISIBLE. THE ILLUMINATION VALUES FOR "GLARE'FREE" LIGHT IN TABLE I ARE ACTUALLY MEANT TO REFER TO THE USE OF PERFECTLY DIFFUSE LIGHTING SUCH AS WOULD OCCUR IN A PHOTOMETRIC SPHERE. WE MAY WELL WONDER TO WHAT EXTENT DIFFERENT MODERN METHODS OF ACTUAL LIGHTING AFFECT TASK DIFFICULTY DUE TO THE REFLECTED GLARE EFFECT. WE HAVE DONE A GREAT DEAL OF WORK ON THIS POINT IN RECENT YEARS.

OUR BASIC TECHNIQUE INVOLVED MAKING PHYSICAL MEASUREMENTS OF THE CONTRAST OF A VISUAL TASK UNDER PERFECTLY DIFFUSE (SPHERE) LIGHTING AND THEN UNDER REAL LIGHTING INSTALLATIONS. IT HAS BEEN FOUND THAT DIFFERENCES IN PHYSICAL CONTRAST PRODUCE CORRESPONDING DIFFERENCES IN TASK DIFFICULTY AS MEASURED WITH THE VISUAL TASK EVALUATOR. HENCE, MEASURES OF PHYSICAL CONTRAST UNDER A REAL LIGHTING INSTALLATION RELATIVE TO PHYSICAL CONTRAST UNDER SPHERE LIGHTING ENABLE US TO COMPUTE MEASURES OF EQUIVALENT CONTRAST WHICH APPLY TO REAL LIGHTING INSTALLATIONS.

THE REQUIRED ILLUMINATION, E_R', FOR A REAL LIGHTING INSTALLATION IS ESTABLISHED FROM THE STANDARD PERFORMANCE CURVE FROM THE VALUE OF $\tilde{C}'$, THE TASK DIFFICULTY FOUND IN THE REAL LIGHTING SITUATION. THE CONTRAST RENDITION FACTOR, CRF, IS DEFINED BY THE RELATION:

$$CRF = \tilde{C}' \,/\, C \tag{1}$$

USUALLY, IT WILL BE FOUND CONVENIENT TO COMPUTE VALUES OF $\tilde{C}'$ FROM THE RELATION

$$\tilde{C}' = \tilde{C} \times CRF \tag{1A}$$

IT WILL OFTEN PROVE HELPFUL TO RECOGNIZE THE CONSTITUENTS OF CRF AS FOLLOWS:

$$CRF = CRF_R \times CRF_l \times CRF_E \tag{2}$$

> WHERE CRF_R IS THE DEGREE OF CONTRAST RENDITION DUE TO ROOM CHARACTERISTICS SUCH AS SIZE AND WALL REFLECTANCE;
>
> CRF_l IS THE DEGREE OF CONTRAST RENDITION DUE TO LAYOUT CHARACTERISTICS SUCH AS LUMINAIRE PLACEMENT; AND
>
> CRF_E, IS THE DEGREE OF CONTRAST RENDITION DUE TO EQUIPMENT CHARACTERISTICS SUCH AS THE POLAR DISTRIBUTIONS OF CANDLE-POWER AND VERTICAL PLANE-POLARIZATION.

IT WILL SOMETIMES BE USEFUL TO EXPRESS THE DEFINITION OF CRF INSTEAD AS:

$$CRF = CRF_R \times CRF_I \tag{3}$$

> WHERE CRF_I IS THE DEGREE OF CONTRAST RENDITION DUE TO ALL ASPECTS OF LIGHTING INSTALLATION.

THIS DEFINITION WILL BE REQUIRED, FOR EXAMPLE, WITH A DIRECT-INDIRECT INSTALLATION WHICH DOES NOT LEND ITSELF TO ANALYSIS IN TERMS OF LAYOUT AND EQUIPMENT VARIABLES.

IT HAS BEEN FOUND THAT MOST REAL LIGHTING INSTALLATIONS REDUCE TASK VISIBILITY IN COMPARISON WITH PERFECTLY DIFFUSE (SPHERE) LIGHTING. PARADOXICAL AS IT MAY SOUND, THE ONLY REMEDY IS TO USE MORE OF THIS COMPARATIVELY POOR LIGHT. THE EYE CAN BE HELPED TO SEE EITHER BY INCREASING TASK CONTRAST OR BY INCREASING ILLUMINATION. TASK CONTRAST IS INDEPENDENT OF THE AMOUNT OF ILLUMINATION USED, BUT DOES DEPEND ON THE METHOD TO PROVIDE IT. IF THE METHOD PROVIDES COMPARATIVELY LITTLE TASK CONTRAST, THEN TASK VISIBILITY MUST BE IMPROVED BY AN INCREASE IN THE AMOUNT OF ILLUMINATION. MORE ILLUMINATION INCREASES VISIBILITY BY SUBTLE CHANGES IN THE OPERATING CHARACTERISTICS OF THE VISUAL SYSTEM. A LITTLE MORE CONTRAST IS AS EFFECTIVE AS A LOT MORE ILLUMINATION. THIS MEANS THAT ILLUMINATION QUALITY, AS MEASURED BY THE TASK CONTRAST A LIGHTING SYSTEM PROVIDES, IS MUCH MORE IMPORTANT THAN ILLUMINATION QUANTITY AS SUCH.

IT HAS ALSO BEEN SHOWN (REF. 3) THAT THE VISUAL DIFFICULTY OF A TASK DEPENDS CRITICALLY UPON THE ANGLE AT WHICH IT IS VIEWED RELATIVE TO A PERPENDICULAR CONSTRUCTED FROM THE SURFACE OF THE TASK. THIS MEANS THAT, AT LEAST AT THE

OUTSET, WE HAVE TO EVALUATE THE QUANTITY OF ILLUMINATION NEEDED FOR A GIVEN VISUAL TASK WHEN VIEWED AT EACH POSSIBLE ANGLE. AND OF COURSE, SINCE THE DIFFICULTY OF A TASK DEPENDS UPON THE PHYSICAL PROPERTIES OF THE INSTALLATION USED TO PRODUCE THE ILLUMINATION, WE HAVE TO SPECIFY THE QUANTITY OF LIGHTING FOR THE TASK FOR EACH ANGLE OF VIEW, UNDER EACH PRACTICAL LIGHTING SYSTEM OF INTEREST.

WE BEGIN BY MEASURING VALUES OF $\tilde{C}$ FOR A TASK AT DIFFERENT VIEWING ANGLES UNDER THE PERFECTLY DIFFUSE LIGHTING PROVIDED WITHIN A SPHERE. THEN, WE MEASURE VALUES OF CRF AT DIFFERENT VIEWING ANGLES IN REAL LIGHTING INSTALLATIONS WITH A PHYSICAL PHOTOMETER. THIS GENERAL METHOD OF ARRIVING AT THE LIGHTING LEVELS NEEDED FOR A SINGLE TASK UNDER DIFFERENT CONDITIONS OF VIEWING AND DIFFERENT METHODS OF LIGHTING HAS BEEN USED TO STUDY THE NO. 2 PENCIL HANDWRITING TASK. IT WILL BE NOTED FROM TABLE I THAT THIS TASK REQUIRED 63 FOOTCANDLES WHEN STUDIED UNDER GLARE-FREE LIGHTING CONDITIONS. IT HAS BEEN SHOWN (REF. 4, 5) THAT TASKS, SUCH AS PENCIL HANDWRITING, ARE VIEWED ON DESK-TOPS AT ANGLES VARYING FROM 0 TO 70 DEGREES FROM PERPENDICULAR. THUS, WE HAVE TO STUDY THE TASK IN QUESTION OVER A WIDE RANGE OF VIEWING ANGLES.

OUR FIRST PROBLEM WAS TO DEVELOP A METHOD FOR PRODUCING STANDARDIZED SAMPLES OF PENCIL HANDWRITING. A CONTROLLED PRESSURE PANTAGRAPH WAS USED TO PRODUCE REPLICA PENCIL HANDWRITING SAMPLES BY RUNNING A STYLUS IN A PLASTIC TEMPLATE MADE FROM A PHOTO-ETCHING OF AN ACTUAL HANDWRITING SAMPLE. A LEAD-BEARING CYLINDER MOVED FREELY WITHIN A BRONZE BUSHING SO THAT THE PRESSURE OF THE LEAD UPON THE PAPER WAS DEPENDENT ALMOST ENTIRELY UPON THE WEIGHT LOADED ON THE CYLINDER. THE PRESSURE WAS VARIED UNTIL SAMPLES WERE PRODUCED WHICH GAVE VALUES OF $\tilde{C}$ UNDER EQUIVALENT ILLUMINATION CONDITIONS EQUAL TO THOSE OBTAINED FOR THE PENCIL HANDWRITING SAMPLES REPORTED IN 1959. THEN, VALUES OF $\tilde{C}$ WERE OBTAINED FOR THE NEW SAMPLES UNDER SPHERE ILLUMINATION, FOR A VARIETY OF VALUES OF VIEWING ANGLE. DUPLICATE HANDWRITING SAMPLES CAN BE MADE FOR THE USE OF OTHER SCIENTIFIC INVESTIGATORS OF THIS PROBLEM.

MEASUREMENTS OF CRF WERE MADE BY PHYSICAL PHOTOMETRY USING A PENCIL DOT AS THE TEST OBJECT, AFTER IT WAS FOUND THAT SUCH MEASUREMENTS WERE VAILID INDICATORS OF THE VISUAL DIFFICULTY OF THE HANDWRITING SAMPLES WHEN VIEWED UNDER DIFFERENT ILLUMINATION CONDITIONS. THE PENCIL DOT USED IS OF PARTICULAR INTEREST BECAUSE OF THE ABUNDANCE OF DATA WHICH HAVE BEEN REPORTED (REF. 2) ON ITS EXPECTED PHYSICAL CONTRAST UNDER DIFFERENT LIGHTING CONDITIONS.

ORIGINALLY, CONTRAST MEASUREMENTS WERE MADE WITH ORDINARY PHOTOMETRIC PROCEDURES USING A LABORATORY MODEL OF THE PRITCHARD PHOTOMETER. A PRECISION ANALYSIS REVEALED THE NEAR IMPOSSIBILITY OF MEASURING DIFFERENCES IN CONTRAST OF 2% OR LESS IN THIS WAY. ACCORDINGLY, SPECIAL PHOTOMETRIC EQUIPMENT WAS USED WHICH HAS BEEN DESIGNATED THE VISUAL TASK PHOTOMETER. THE TEST OBJECT

CAN BE SUBSTITUTED FOR THE PAPER BACKGROUND QUICKLY BY MEANS OF SOLENOID-DRIVEN MICROSTAGE. THE OPERATOR OF THE DEVICE HAS TO SATISFY A DOUBLE-NULL CONDITION. WHEN THE BACKGROUND IS IN PLACE, HE ADJUSTS THE OUTPUT FROM THE LABORATORY MODEL PRITCHARD PHOTOMETER UNTIL IT MATCHES A REFERENCE VOLTAGE. WHEN THE TEST OBJECT IS IN PLACE, HE ADJUSTS A SECOND REFERENCE VOLTAGE UNTIL IT MATCHES THE OUTPUT FROM THE PHOTOMETER. THE RATIO OF THE REFERENCE VOLTAGE IS THEN READ BY MEANS OF A PRECISION POTENTIOMETER, AND EQUALS THE DESIRED CONTRAST VALUE. THE DEVICE PROVIDES MEASURES OF TASK CONTRAST TO A PRECISION OF $\pm$ 0.1%.

A LIGHTING TEST ROOM WAS SET UP ON AN OPEN SECTION OF A LARGE FACTORY AREA LOCATED CONVENIENTLY NEAR THE CAMPUS OF COLUMBUS. PLASTER-BOARD WALLS WERE CONSTRUCTED TO PROVIDE AN ENVIRONMENT OF CONTROLLABLE REFLECTANCE. THE ROOM MEASURED 28 X 28 FEET INSIDE. A FULL LUMINOUS CEILING WAS INSTALLED OVER THE ENTIRE TEST ROOM. MASKING TILES CUT THE USABLE LUMINOUS AREA TO 26 X 26 FEET. A T-BAR SUSPENSION SYSTEM WAS USED SO THAT ANY TRANSLUCENT OR OPAQUE MATERIAL OF NOMINAL 2 X 2 FOOT DIMENSIONS COULD BE MOUNTED IN THE CEILING. THE FLOOR-TO-CEILING HEIGHT WAS 108 INCHES.

THE VISUAL TASK PHOTOMETER WAS LOCATED IN THE CENTER OF THE ROOM LEFT-TO-RIGHT NEAR ONE SIDE. THE TEST OBJECT WAS PLACED AT A POINT 3 FEET FROM THE EDGE OF THE LUMINOUS AREA. A TOTAL OF TWELVE 2-FOOT ROWS OF LUMINOUS SOURCES COULD BE USED, BUT ONLY THE CENTER 9 ROWS WERE USED. THE WALLS WERE PAINTED A YELLOWISH PAINT WITH REFLECTANCE OF APPROXIMATELY 50%. THE FLOORS WERE CLEANED CONCRETE, SOMEWHAT NON-UNIFORM IN REFLECTANCE, WITH AN AVERAGE VALUE OF ABOUT 15%. THE TILES IN THE CEILING HAD A REFLECTANCE OF ABOUT 80%.

LIGHTING MATERIALS WERE OBTAINED WITH A DIFFERENT PHYSICAL CHARACTERISTICS AS POSSIBLE, CONSIDERING THAT THE MATERIALS HAD TO BE USED IN A FULL LUMINOUS CEILING. THREE MATERIALS WERE OBTAINED: DIFFUSERS, MULTILAYER POLARIZERS, AND EGGCRATE LOUVERS TO PROVIDE LIGHT CONTROL. VALUES OF CRF WERE OBTAINED BY DIVIDING THE VALUES OF TASK CONTRAST OBTAINED IN THE TEST ROOM BY VALUES OBTAINED IN A SPHERE AT THE SAME VIEWING ANGLES. THEN, THE VALUES OF CRF WERE USED TO COMPUTE VALUES OF $\tilde{C}'$ AND E_R'.

TABLE II CONTAINS INDIVIDUAL ILLUMINATION VALUES FOR EACH OF FOUR LAYOUTS OF EACH OF THE THREE LIGHTING MATERIALS, FOR EACH OF FIVE VIEWING ANGLES. VALUES FOR THE THEORETICAL LAMBERTIAN MATERIAL WERE OBTAINED FROM THOSE FOR THE DIFFUSERS BY THEORETICAL CALCULATION. IT IS OBVIOUS THAT VIEWING ANGLE, LAYOUT, AND LIGHTING MATERIAL ALL INFLUENCE THE REQUIRED ILLUMINATION LEVEL GROSSLY.

ALTHOUGH NOTHING SHORT OF THE INDIVIDUAL ILLUMINATION VALUES AT DIFFERENT VIEWING ANGLES CAN TELL THE WHOLE STORY, IT WILL BE USEFUL TO PRESENT VALUES OF $\overline{E}_R'$, THE REQUIRED ILLUMINATION VALUE OBTAINED BY WEIGHTING THE VALUES OF E_R' FOR INDIVIDUAL VIEWING ANGLES. A METHOD OF WEIGHTING HAS BEEN DEVELOPED WHICH

IS BASED UPON THE FREQUENCY OF USAGE OF DIFFERENT VIEWING ANGLES. PERCENTAGE WEIGHTS FOR THE FOUR MAJOR VIEWING ANGLES ARE AS FOLLOWS: 10^{o} - 11.0%; 25^{o} - 50.3%; 40^{o} - 34.0%; AND 60^{0} - 4.7%. THE VALUES PRESENTED IN TABLE III WERE OBTAINED BY APPLYING THESE WEIGHTS TO THE INDIVIDUAL VALUES PRESENTED IN TABLE II. (VALUES HAVE NOT BEEN PRESENTED FOR THE 1 ROW CASE. THE > SIGNS IN TABLE II SIGNIFY THAT, EXCEPT WITH MULTILAYER POLARIZERS, THE 1 ROW INSTALLATIONS PRODUCE SUCH BAD TASK VISIBILITY THAT THE ILLUMINATION REQUIREMENTS FOR THE TASK ARE GREATER THAN THE LARGEST VALUE WE HAVE EVER STUDIED AND HENCE INDETERMINANT).

THE IMPORTANCE OF ILLUMINATION QUALITY MAY BE JUDGED BY THE DATA SUMMARIZED IN TABLE III. IT IS TO BE REMEMBERED THAT THE REQUIRED FOOTCANDLES ARE FOR THE NO. 2 PENCIL TASK FOR WHICH THE GLARE-FREE ILLUMINATION REQUIREMENTS WAS ORIGINALLY GIVEN AS 63.0 FOOTCANDLES. THE VALUES REVEAL THAT THE REQUIREMENT FOR ILLUMINATION QUANTITY DEPENDS IMPORTANTLY UPON BOTH THE LAYOUT OF CEILING-MOUNTED LIGHT SOURCES, AND THE LIGHTING MATERIAL USED IN EACH LAYOUT. FOR BEST TASK CONTRAST AND HENCE BEST VISIBILITY, LIGHT SHOULD COME TO THE TASK FROM AS LARGE A PERCENTAGE OF THE CEILING AS POSSIBLE. INCREASING THE AREA OF THE SOURCE OF LIGHT REDUCES THE DELETERIOUS EFFECT OF A LIGHT RAY COMING FROM JUST THE WRONG ANGLE WHICH WILL TEND TO CONCEAL THE TASK BENEATH A VEIL OF REFLECTED GLARE. THE LIGHT-CONTROL MATERIAL IS A LITTLE BETTER THAN THE DIFFUSER MATERIAL IN THE SAME LAYOUTS, BECAUSE THE ANGLE OF EMERGENCE LIGHT CAN BE CONTROLLED SO AS TO REDUCE REFLECTED GLARE. THE MULTILAYER POLARIZERS HAVE THIS LIGHT-CONTROL FEATURE AND, IN ADDITION, PRODUCE A PREPONDERANCE OF VERTICALLY PLANE-POLARIZED LIGHT. IT IS A PHYSICAL FACT THAT VERTICALLY PLANE-POLARIZED LIGHT REDUCES REFLECTED GLARE, THUS INCREASING THE TASK CONTRAST AND VISIBILITY. THE DATA IN TABLE III SHOW THAT WITH THE BEST QUALITY LIGHT, CONSIDERABLY LOWER FOOT-CANDLES CAN BE USED THAN WITH OTHER METHODS OF ILLUMINATION. THE GREATER VISUAL EFFECTIVENESS OF LIGHTING INSTALLATIONS PRODUCING GOOD VISIBILITY THROUGH HIGHER TASK CONTRAST CERTAINLY LOOMS LARGE IN TERMS OF THE ECONOMICS OF INSTALLING AND MAINTAINING THE LIGHT LEVELS REQUIRED WITH THE VARIOUS INSTALLATIONS.

THE ABSOLUTE VALUES OF TABLE III DEPEND, OF COURSE, UPON THE ORIGINAL VALUE OF 63.0 FOOTCANDLES FOR THE PENCIL TASK UNDER GLARE-FREE LIGHT WHICH DEPENDS IN TURN UPON THE FIELD FACTOR OF 15. THUS, THESE ABSOLUTE VALUES MAY BE SUBJECT TO SOME DEGREE OF ARGUMENT. THE RELATIVE VALUES, HOWEVER, DEPEND BUT LITTLE UPON ANYTHING EXCEPT THE PHYSICAL FACTS ABOUT TASK CONTRAST UNDER DIFFERENT REAL LIGHTING INSTALLATIONS. THUS WE CAN SAY FLATLY THAT THE BEST LIGHTING INSTALLATION CAN PROVIDE A GIVEN VISIBILITY CRITERION WITH LITTLE MORE THAN ONE-FOURTH OF THE LIGHT LEVEL REQUIRED WITH THE WORST LIGHTING INSTALLATION. THIS DIFFERENCE IN THE LEVEL OF ILLUMINATION REQUIRED FOR THE SAME TASK VISIBILITY SEEMS TO ME A MOST DIRECT MEASURE OF THE RELATIVE MERIT OF THE LIGHTING INSTALLATIONS INVOLVED. WE CAN SAY THAT THE ILLUMINATION COMING FROM THE BEST SYSTEM HAS APPROXIMATELY FOUR TIMES AS GREAT A VISUAL EFFECTIVENESS AS THE ILLUMINATION COMING FROM THE WORST SYSTEM.

IT HAS BEEN SHOWN ELSEWHERE (REF. 3) THAT WE CAN PREDICT THE RESULTS OF FIELD TESTS OF TASK CONTRAST SUCH AS THESE FROM CALCULATIONS BASED UPON THE PHYSICAL PROPERTIES OF BOTH TASKS AND LIGHTING MATERIALS. SPECIFICALLY, WE CAN PREDICT THE DIFFERENCES IN TASK CONTRAST TO BE EXPECTED WITH DIFFERENT LIGHTING MATERIALS; THAT IS, WE CAN PREDICT VALUES OF CRF. WE HAVE TO DETERMINE VALUES OF CRF_R AND CRF_1 BY ACTUAL FIELD TESTS WITH THE TASK OF INTEREST. THIS MEANS THAT LIGHTING SYSTEMS CAN BE EVALUATED BY CALCULATIONS DURING THE DESIGN PHASE. THE FOOTCANDLE LEVEL FOR THE DESIRED LEVEL OF TASK VISIBILITY MAY FIRST BE DETERMINED BY CALCULATIONS OF CRF, AND THE INSTALLATION IS THEN LAID OUT SO AS TO PROVIDE THIS ILLUMINATION LEVEL. FIELD TESTS ON THE COMPLETED INSTALLATION WILL REVEAL THE CONFORMITY OF THE TASK VISIBILITY OBTAINED IN THE INSTALLATION TO THE EXPECTED VALUE. THIS PROCESS REPRESENTS THE COMPLETE EVALUATION OF A LIGHTING PROBLEM BY A TECHNIQUE OF VISION ENGINEERING.

IV. LIGHTING VARIABLES AND DIRECT COMFORT

IN ADDITION TO AVOIDING INDIRECT DISCOMFORT WHICH RESULTS FROM TRYING TO SEE IN BAD LIGHT, WE MUST PROVIDE LIGHT IN SUCH A WAY AS TO AVOID DIRECT DISCOMFORT. THE EXPERIENCE OF DIRECT DISCOMFORT OCCURS WHEN WE ENTER A ROOM WITH EXCESSIVELY BRIGHT LIGHT SOURCES, WHICH ARE SAID TO PRODUCE DISCOMFORT DUE TO "DIRECT GLARE" (AS DISTINGUISHED FROM REFLECTED GLARE).

IT IS POSSIBLE TO SET A REASONABLE LIMIT ON THE BRIGHTNESS A CEILING-MOUNTED LIGHT SOURCE MAY REACH BEFORE PRODUCING GLARE DISCOMFORT. THE ALLOWABLE BRIGHTNESS DEPENDS UPON THE POINT ON THE CEILING BEING CONSIDERED WITH RESPECT TO THE LOCATION OF THE USER'S EYES. POINTS ON THE CEILING ACROSS THE ROOM ARE MUCH MORE GLARING THAN POINTS MORE NEARLY DIRECTLY OVERHEAD, PRESUMABLY BECAUSE THE FORMER ARE NEARER THE LINE-OF-SIGHT USED WHEN LOOKING CASUALLY ABOUT A ROOM. THUS, POINTS ON THE CEILING ACROSS THE ROOM CANNOT BE ALLOWED TO BE AS BRIGHT AS POINTS MORE NEARLY OVERHEAD. THIS CHARACTERISTIC OF A LIGHTING SYSTEM MAY BE DESCRIBED IN TERMS OF THE BRIGHTNESS ALOWABLE FROM EACH ELEMENT OF CEILING AT DIFFERENT ANGLES FROM VERTICALLY BENEATH IT. THE BRIGHTNESS AT LARGE ANGLES FROM VERTICAL IS THE BRIGHTNESS WHICH WILL BE SEEN FROM POINTS ON THE CEILING ACROSS THE ROOM. THE ALLOWABLE BRIGHTNESS OF 85 DEGREES FROM VERTICAL IS ABOUT 165 FOOT-LAMBERTS; AT 45 DEGREES FROM VERTICAL, THE VALUE IS 750 FOOT-LAMBERTS. THUS, MUCH MORE BRIGHTNESS CAN BE TOLERATED WITHOUT DISCOMFORT AT SOME ANGLES THAN AT OTHERS. THE FUNDAMENTAL BASIS FOR A LIMITATION ON BRIGHTNESS TO AVOID DIRECT GLARE DISCOMFORT MAY BE FOUND IN THE PRINCIPLES OF THE PHYSIOLOGY OF THE EYE. THIS TYPE OF DISCOMFORT IS AT LEAST LARGELY DUE TO THE CONSTRICTION OF THE EYE PUPIL. THUS, THE BRIGHTNESS LIMITATION FOR ELEMENTS OF THE CEILING LOCATED IN DIFFERENT POINTS IN THE SPACE ABOUT US DEPENDS UPON THE EFFECTIVENESS OF THESE ELEMENTS IN STIMULATING PUPILLARY CONSTRICTION.

THESE FACTS ABOUT DISCOMFORT GLARE ENABLE US TO EVALUATE LIGHTING EQUIPMENT IN A VERY GENERAL WAY. WE MUST HAVE PHYSICAL DATA ON THE RELATIVE BRIGHTNESS

OF A PIECE OF LIGHTING EQUIPMENT AT DIFFERENT ANGLES FROM VERTICAL (NORMAL). THEN, WE CAN CONSIDER THAT WE ARE ALLOWED TO INCREASE THE ACTUAL BRIGHTNESS OF THE EQUIPMENT UNTIL THE BRIGHTNESS AT SOME ANGLE JUST REACHES THE ALLOWABLE LIMIT. ONCE THE ALLOWABLE BRIGHTNESS FOR A LIGHT SOURCE HAS BEEN DETERMINED, IT IS A SIMPLE MANNER TO COMPUTE THE ILLUMINATION PRODUCED BY A LIGHTING INSTALLATION LIMITED IN THIS WAY. THIS VALUE OF ILLUMINATION MAY BE CONSIDERED THE ILLUMINATION LEVEL ALLOWABLE WITHOUT GLARE DISCOMFORT. LIGHT-CONTROL MATERIALS ALLOW US TO HAVE MORE FOOTCANDLES WITHOUT DISCOMFORT THAN PERFECT DIFFUSERS USED IN THE SAME LAYOUT OF DISCRETE LUMINAIRES. THIS IS BECAUSE THE LIGHT-CONTROL MATERIALS REDUCE BRIGHTNESS AT THE LARGE ANGLES FROM NORMAL AT WHICH THE EYE CANNOT TOLERATE HIGH BRIGHTNESS. THE MULTILAYER POLARIZERS HAVE THE SAME EFFECT TO AN EVEN GREATER EXTENT.

HIGHER ILLUMINATION LEVELS ARE ALLOWABLE WHEN MORE OF THE CEILING IS COVERED WITH LIGHT SOURCES SIMPLY BECAUSE OF THE LARGE AREA OF LIGHT SOURCE INVOLVED. SPREADING OUT THE LIGHT SOURCE INCREASES THE ALLOWABLE ILLUMINATION BY REDUCING THE BRIGHTNESS AT ANY POINT ON THE CEILING NEEDED TO PRODUCE A GIVEN NUMBER OF FOOTCANDLES.

WE MAY DRAW THESE GENERAL CONCLUSIONS ABOUT THE RELATIVE LEVELS OF ILLUMINATION ALLOWABLE WITHOUT DIRECT GLARE DISCOMFORT WITH DIFFERENT LIGHTING SYSTEMS. HOWEVER, WE DO NOT AS YET HAVE SUFFICIENT VISUAL DATA TO ALLOW THE ESTABLISHMENT OF PRECISE VALUES OF ALLOWABLE ILLUMINATION FOR DIFFERENT INSTALLATIONS. WE CAN SAY THAT THE BEST MATERIAL TESTED TO DATE (MULTILAYER POLARIZERS) PERMITS USE OF MORE THAN THREE TIMES AS MANY FOOTCANDLES WITHOUT DISCOMFORT AS THE WORST (PERFECT DIFFUSERS) IN EACH POSSIBLE LAYOUT.

V. GENERAL REMARKS ABOUT ILLUMINATION STANDARDS.

THROUGHOUT THE EARLIER SECTIONS OF THIS PAPER, THE THEME HAS REOCCURRED THAT WE CAN BE MUCH MORE POSITIVE ABOUT RELATIVE LIGHTING REQUIREMENTS UNDER DIFFERENT CONDITIONS THAN ABSOLUTE REQUIREMENTS. WE ARE CERTAIN THAT DIFFERENT TASKS REQUIRE VERY DIFFERENT LIGHTING LEVELS, LESS CERTAIN EXACTLY HOW MANY FOOTCANDLES WE MUST HAVE FOR ANY TASK. WE ARE CERTAIN THAT LIGHTING SYSTEMS PROVIDING GOOD TASK CONTRAST CAN PROVIDE ADEQUATE VISIBILITY WITH MUCH LESS LIGHT THAN IS NEEDED WITH SYSTEM PROVIDING POOR CONTRAST. WE ARE CERTAIN THAT THE ALLOWABLE FOOTCANDLES ARE MUCH HIGHER WITH THE BEST THAN WITH THE WORST LIGHTING MATERIALS. THESE STATEMENTS EMPHASIZE THE NEED FOR A MORE FLEXIBLE VIEW ON LIGHTING REQUIREMENTS THAN IS IMPLIED BY A SINGLE FOOTCANDLE STANDARD. THE DATA PRESENTED IN THE PAPER SHOULD PROVIDE THE LIGHTING DESIGNER WITH SOME IDEA OF WHAT IS INVOLVED WHEN A GIVEN LIGHTING SYSTEM IS BEING CONSIDERED. IT IS CLEAR THAT SOME LIGHTING SYSTEMS ARE VASTLY SUPERIOR TO OTHERS PRODUCING THE SAME NUMBER OF FOOTCANDLES. THE WORST METHOD OF LIGHTING INVOLVES USE OF A FEW ROWS OF LUMINAIRES FITTED WITH PERFECTLY DIFFUSING PANELS. IF SUCH A SYSTEM COVERS ONLY 33% OF THE CEILING WITH LUMINAIRES (THE 3-ROW CASE), THE PENCIL TASK REQUIRES 261 FOOTCANDLES. TO MAKE MATTERS WORSE, THE HIGH BRIGHTNESS

OF THESE LUMINAIRES PARTICULARLY AT ANGLES FAR FROM THE NORMAL SEVERELY LIMITS THE ALLOWABLE ILLUMINATION. MATTERS CAN BE MUCH IMPROVED BY INCREASING THE CEILING COVERAGE OF THE LIGHT SOURCES. TOTAL CEILING COVERAGE (THE 9-ROW CASE) CAN REPRESENT THE CASE OF TOTALLY INDIRECT LIGHTING, OR A LUMINOUS CEILING, OR CLOSELY-PACKED LUMINAIRES. IN THIS CASE, WE REQUIRE ONLY 138 FOOTCANDLES FOR THE PENCIL TASK WHEN PERFECT DIFFUSERS ARE USED. THE LIGHT CONTROL PANELS ARE HELPFUL BOTH IN REDUCING REQUIRED FOOTCANDLES AND IN INCREASING ALLOWABLE FOOTCANDLES, BUT THE MULTILAYER POLARIZERS ARE MUCH BETTER STILL. THE REQUIRED FOOTCANDLES CAN BE REDUCED TO AS LITTLE AS ONE-THIRD AND THE ALLOWABLE FOOTCANDLES INCREASED BY THREE TIMES WHEN THESE PANELS ARE USED IN PLACE OF PERFECT DIFFUSERS. THE BEST SYSTEM FROM BOTH POINTS OF VIEW IS A FULL CEILING OF MULTILAYER POLARIZERS.

THE OVER-RIDING IMPORTANCE OF LIGHTING QUALITY LEADS ME TO RECOMMEND STRONGLY THAT THIS ASPECT OF DIFFERENT SYSTEMS BE GIVEN FIRST CONSIDERATION IN LIGHTING DESIGN. THE DESIGN MUST HAVE QUALITY AND THEN THE QUANTITY SHOULD BE INCREASED TO THE LIMIT IMPOSED BY ARCHITECTURAL AND COST FACTORS. PROVIDED WE BEGIN WITH QUALITY, THE "MORE LIGHT THE BETTER SIGHT". AS FOOTCANDLES INCREASE, MORE AND MORE TASKS WILL BECOME ADEQUATELY VISIBLE. WITH QUALITY, INCREASES IN LIGHT INTENSITY WILL PROVE HELPFUL UP TO AT LEAST 500 FOOTCANDLES.

AT WHAT ILLUMINATION LEVEL SHOULD QUANTITY BE SET? THE SELECTION IS SOMEWHAT ARBITRARY. THE SIMPLEST VISUAL TASKS CAN BE PERFORMED ADEQUATELY WITH LESS THAN 10 FOOTCANDLES. AN INCREASE TO 30 FOOTCANDLES INCREASES CONSIDERABLY THE NUMBER OF TASKS WHICH WILL BE ADEQUATELY VISIBLE. A FURTHER INCREASE TO 50 FOOTCANDLES BRINGS MANY MORE TASKS TO ADEQUATE VISIBILITY. STILL MORE WILL BE ADEQUATELY VISIBLE AT 70 FOOTCANDLES. MOST VISUAL TASKS CAN BE PERFORMED ADEQUATELY AT 150 FOOTCANDLES. ONLY THE MOST DIFFICULT TASKS REQUIRE MORE THAN 500 FOOTCANDLES. LET EACH COUNTRY DECIDE HOW FAR ALONG THIS ROAD THEY WISH TO TRAVEL.

ONCE THE LEVEL OF FOOTCANDLES HAS BEEN SET APPROXIMATELY, THE VALUES NEEDED FOR DIFFERENT LIGHTING INSTALLATIONS MAY BE DEDUCED BY USING THE RELATIONS AMONG THE DIFFERENT VALUES SHOWN IN TABLE III. FOR EXAMPLE, IF THE BASIC LIGHTING STANDARD IS TO BE SET AT 30, FOOTCANDLES INSTEAD OF THE VALUE OF 63. BUILT INTO THE TABLE, EACH VALUE IN TABLE III SHOULD BE MULTIPLIED BY THE RATIO 30/63. SUCH A USE OF THE DATA DOES NOT CHANGE AT ALL THE ORDER OF MERIT OF VARIOUS LIGHTING SYSTEMS NOR THE RELATIVE DIFFERENCES IN FOOTCANDLES REQUIRED WITH THE DIFFERENT SYSTEMS.

ALTHOUGH COLOR WAS NOTED AS ONE OF THE PHYSICAL CHARACTERISTICS OF LIGHTING, NOTHING FURTHER HAS BEEN SAID ABOUT IT. WE KNOW THAT THE COLOR OF LIGHTING HAS ESSENTIALLY NO EFFECT UPON TASK VISIBILITY. IT HAS SMALL EFFECT UPON DIRECT DISCOMFORT, THE WARMER COLORS PRODUCING THE LEAST DISCOMFORT. COLOR, OF COURSE, HAS VERY IMPORTANT EFFECTS UPON THE PLEASANTNESS OF VISUAL ENVIRONMENT. HERE AGAIN WE KNOW LESS ABOUT THIS ASPECT OF LIGHT THAN WE SHOULD BECAUSE OF REAL DIFFICULTIES ENCOUNTERED IN MEASURING THE PLEASANTNESS OF LIGHTING.

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TABLE I

LIGHTING REQUIREMENTS FOR SAMPLE TASKS BASED ON 1959 STANDARDS FOR "GLARE FREE" LIGHT

TASK DESCRIPTION	REQUIRED FOOTCANDLES
10-POINT TEXTYPE PRINT	0.9
8-POINT TEXTYPE PRINT	1.1
INK WRITING ON WHITE PAPER	1.4
12 EASIEST SPIRIT-DUPLICATED SAMPLES	2.1
PRINTED NUMERALS	8.3
NO. 2 PENCIL ON WHITE PAPER	63.0
NO. 3 PENCIL ON WHITE PAPER	76.5
5TH CARBON COPY OF TYPED MATERIAL	133.0
12 MOST DIFFICULT SPIRIT-DUPLICATED SAMPLES	141.0
BROKEN WHITE THREAD	487.0

TABLE II

REQUIRED INDIVIDUAL FOOTCANDLES FOR NO.2 PENCIL TASK

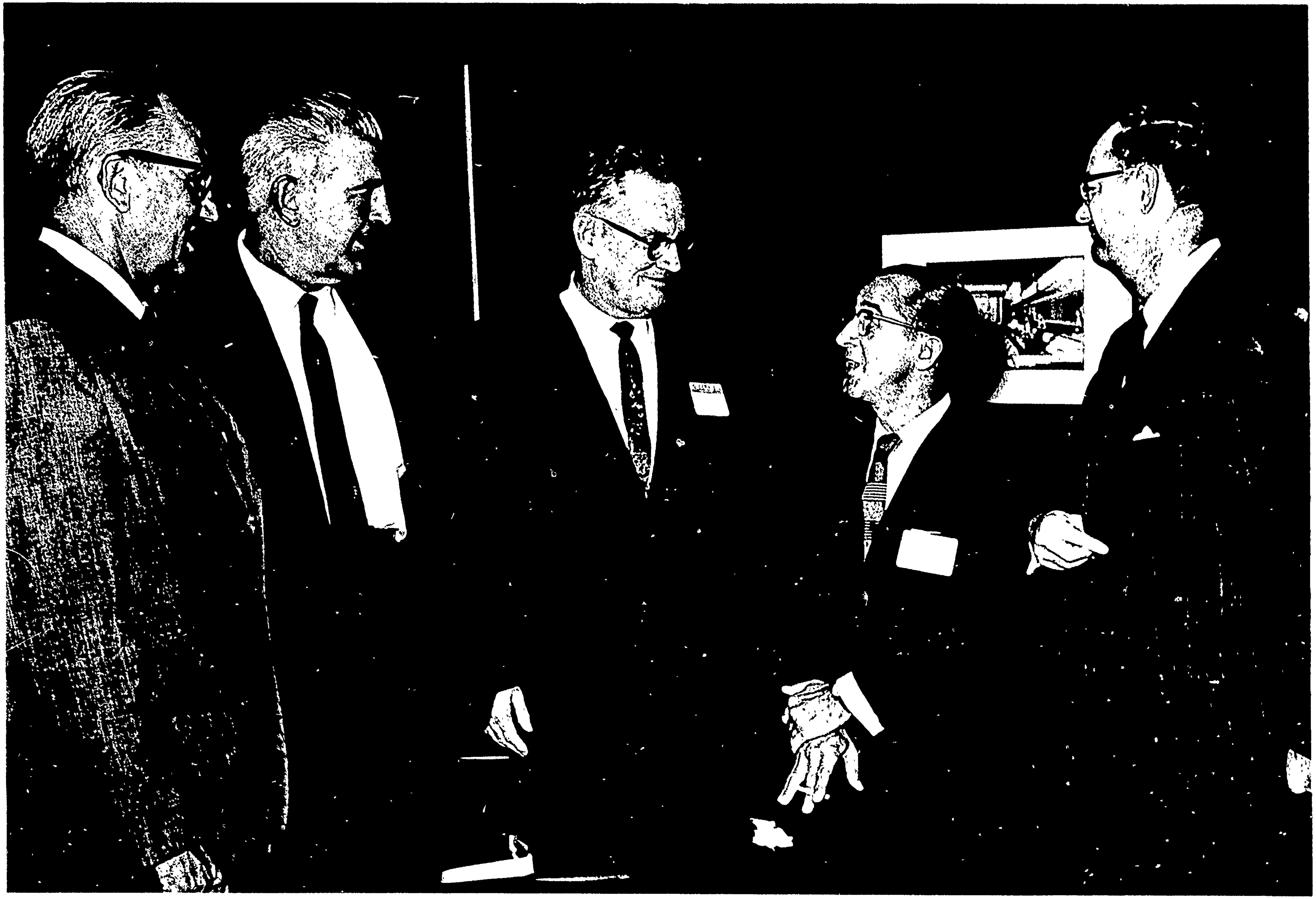
VIEWING ANGLE (DEGREES)

LAYOUT	10	25	40	50	60
		A. THEORETICAL LAMBERTIAN MATERIAL			
9 ROWS	29.6	48.4	134		1,380
5 ROWS	30.0	49.4	164		1,562
3 ROWS	32.4	59.2	228		3,200
1 ROW	158.	300.	1,682		>4,150
		B. DIFFUSERS			
9 ROWS	31.4	49.8	118.	248.	910
5 ROWS	32.5	52.3	137.	272.	942.
3 ROWS	35.	59.7	184.	332.	1,340
1 ROW	175.	300.	639	1,448	>4,150
		C. MULTILAYER POLARIZERS			
9 ROWS	28.0	45.0	87.0	144.	382.
5 ROWS	30.5	46.2	88.7	147.	394.
3 ROWS	34.4	49.3	109.	172.	447.
1 ROW	62.	268.	296.	510.	1,562
		D. EGGCRATE LOUVRES			
9 ROWS	32.8	55.4	120.	248.	805.
5 ROWS	35.4	59.7	131.	236.	774.
3 ROWS	38.2	70.9	174.	300.	1,150.
1 ROW	239.	414.	567.	826.	> 4,150.

TABLE III

REQUIRED WEIGHTED FOOTCANDLES FOR NO. 2 PENCIL TASK

LAYOUT	THEORETICAL LAMBERTIAN MATERIAL	DIFFUSERS	MULTILAYER POLARIZERS	EGGCRATE LOUVRES
9 ROWS	138.	111.	73.2	110.
5 ROWS	157.	121.	75.3	115.
3 ROWS	261.	159.	87.0	153.



LEFT TO RIGHT:

MR. D. R. SNYDER, ASSISTANT SUPERINTENDENT OF PHYSICAL PLANT, DADE COUNTY SCHOOLS, DR. JOE HALL, SUPERINTENDENT DADE COUNTY PUBLIC SCHOOLS, MR. RICHARD O. ROBERTS, DISTRICT SUPERINTENDENT, DADE COUNTY PUBLIC SCHOOLS, MR. ANDREW J. FERENDINO, ARCHITECT TO THE DADE COUNTY BOARD OF PUBLIC INSTRUCTION, PANCOAST, FERENDINO, GRAFTON & SKEELS, MR. EDWARD E. HURST, ASSISTANT SUPERINTENDENT FOR BUSINESS SERVICES, DADE COUNTY PUBLIC SCHOOLS.

LEFT TO RIGHT:

MR. AL COSENTINO, ELECTRICAL ENGINEER, COSENTINO & GAM, MR. E.N. NICOLADEIS, ELECTRICAL ENGINEER, DIGNUM ASSOCIATES.
MRS. OLIVE BLACKWELL, DR. H. RICHARD BLACKWELL, DIRECTOR INSTITUTE FOR RESEARCH IN VISION, OHIO STATE UNIVERSITY.

LEFT TO RIGHT:
MR. ROBERT M. LITTLE, ARCHITECT, MR. WILLIAM LYON, ARCHITECT, WATSON, DEUTSCHMAN & KRUSE, ARCHITECTS & ENGINEERS, MR. H. MAXWELL PARISH, ARCHITECT, MR. ALFRED B. PARKER, ARCHITECT, MR. PINSON WHIDDON, ASSISTANT ARCHITECT TO THE DADE COUNTY BOARD OF PUBLIC INSTRUCTION, PANCOAST, FERENDINO, GRAFTON & SKEELS, MR. THEODORE GOTTFRIED, ARCHITECT.

LEFT TO RIGHT:
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LEFT TO RIGHT:
MR. JOHN T. FOSTER, ARCHITECT, TECHNICAL STUDIES AND INSPECTION, STATE DEPT. OF EDUCATION, MR. JAMES H. CHURCH, ARCHITECT, DIRECTOR OF SCHOOL CONSTRUCTION RESEARCH, PANCOAST, FERENDINO, GRAFTON & SKEELS.

Visual Benefits of Polarized Light

H. RICHARD BLACKWELL PH D

Director, Institute for Research in Vision, Ohio State University

IN RECENT YEARS, research studies of the operating characteristics of the human visual sense have provided a new basis for evaluating lighting in terms of its quantitative effect upon vision. Thus much, if not most, of what used to be considered *illuminating engineering* is becoming recognized as *vision engineering*. The design of efficient equipment for producing and distributing light remains the province of illuminating engineering, but evaluating the effectiveness of lighting in stimulating human vision must become the function of vision research specialists, not of electrical engineers. Vision engineering provides a quantitative method for evaluating all aspects of lighting which have been designated *quantity* and *quality*. Visual criteria include ease of seeing, comfort and pleasantness.

Development of this new field has been made possible by research studies conducted in various laboratories in recent years. Perhaps the cornerstone of vision engineering is the work completed by the author in 1958,[1] which defined the visual effectiveness of illumination quantity. The second most important portion of the work may well be the author's 1963 study of the visual significance of reflected glare.[2, 3] Taken together, these studies provide a quantitative basis for evaluating ease of seeing provided by lighting systems differing both in quantity and quality.

The recent study of reflected glare showed that well-designed lighting systems can increase ease of seeing to a substantial extent and can substitute lighting *quality* in place of considerable increases in lighting *quantity*. Effective lighting is describable in terms of size and placement of illumination sources, spatial

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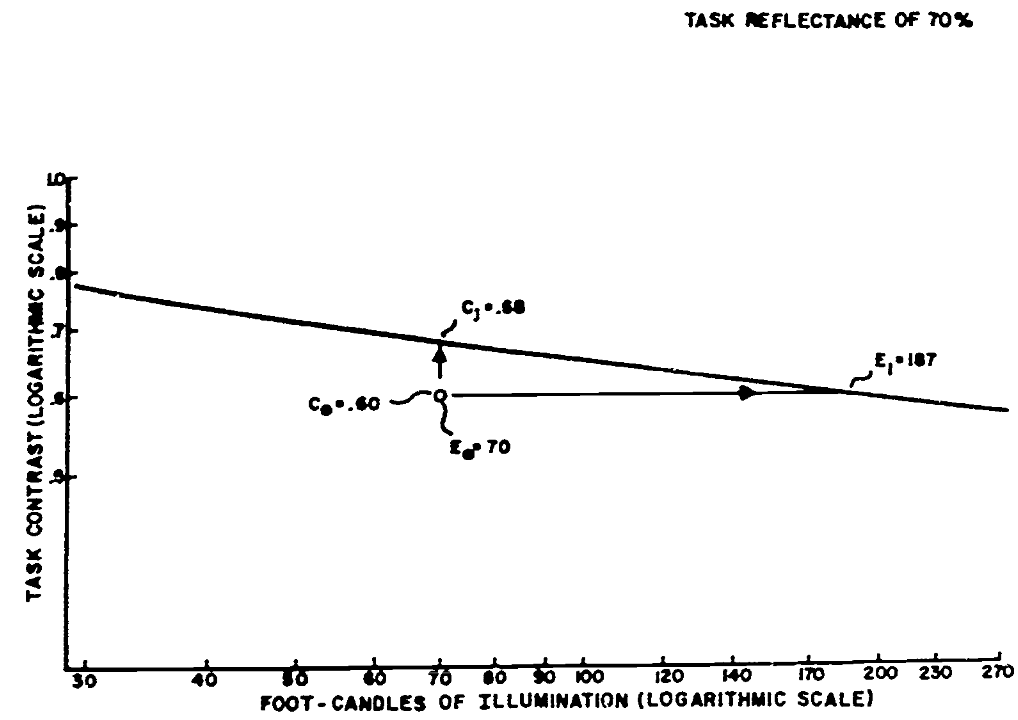

Fig 1:
Operating characteristics of human vision, demonstrating the large quantity of light needed to improve the ease of seeing as much as improvements in task contrast due to high-quality lighting

light distribution from each source and degree to which the illumination is *vertically plane-polarized.* Since this last characteristic is somewhat unfamiliar in the field of lighting, this article will describe the general principles which govern the visual effectiveness of polarized light. More detailed quantitative data on this new dimension of modern lighting will be found in a series of articles describing vision engineering.[8] Let us begin with a brief description of the physics of the subject.

The Physics of Polarized Light

We may all remember dimly from school days that light does not really travel in straight lines, but consists of complex waveforms propagated through space. If we could stand at one point in space and watch light waves pass by in slow motion, we would see that light traces out wave patterns, describable in terms of the spacing between successive waves. Light waves which are widely spaced are called *long* and look red to the eye, whereas narrowly spaced light waves are called *short* and look blue. Thus, the wavelength of the light pattern, viewed lengthwise of the beam, defines the color of light. If we stood right in the path of the oncoming light and watched it approach, we would see the light beam trace out transverse wave patterns. The mathematical character of these patterns viewed head-on defines the polarization of the light. Together with the quantity of light, polarization and color are the fundamental attributes of light.

The simplest kind of polarized light is called plane-polarized, which means that the waveforms viewed head-on represent vibrations in simple planes, rather than in cylinders or more complex patterns. Pure horizontally plane-polarized light would be seen to vibrate only left and right as it approached, whereas pure vertically plane-polarized light would vibrate only up and down. Most light would vibrate to some extent in all directions, and thus could be described by a vector analysis as being partially horizontally and partially vertically plane-polarized.

Light reflected directly from solid flat surfaces tends to be predominantly horizontally plane-polarized, whereas light which is first absorbed and then reflected will generally be unpolarized. The light which is directly reflected tends to hide the properties of the material behind a veil of light, as we have all seen in the case of the strong reflections of light from water and snow. We may greatly reduce this veiling reflection by the use of "polarized" sunglasses. The principle is simple. The reflected light is predominantly horizontally plane-polarized. The sunglasses absorb horizontally plane-polarized light and hence dim the veiling reflection considerably, enabling us to see behind the light-veil, using the vertically plane-polarized light emitted by the objects. Actually, the eye cannot detect that light is plane-polarized. In the case just described, nature produced a light-veil of horizontally plane-polarized light which was absorbed by correctly designed sunglasses, thus revealing what was otherwise hidden behind the veil.

The physics of polarized light is somewhat different when polarized sources are used for interior lighting. If we place a sheet of sunglass material over a ceiling-mounted source, the emitted light will be plane-polarized, but the plane of polarization will be different at different points in the room. In one position, the light will vibrate in a plane which may be described as the vertical, but at a position 90° away, the light will vibrate in the horizontal plane. In visual tasks located on horizontal surfaces, horizontally plane-polarized light tends to be reflected from the surface in the form of a light-veil, whereas vertically plane-polarized light tends to be absorbed and re-emitted. As in the natural scene, the reflected light-veil conceals the characteristics of materials, whereas the light which is absorbed and re-emitted reveals these characteristics. Thus, use of vertically plane-polarized light from the source tends to reduce the

light-veil and reveal the characteristics of the visual task, in a manner similar to that by which the polarized sunglasses reveal the characteristics of the outdoor scene. The difficulty is that sunglass material has a beneficial effect at some locations in the room, and an equally deleterious effect at other locations in the room. This is no doubt a good reason why sunglass material has never been adopted for ceiling-mounted light sources, although there are several additional reasons. Sunglass material achieves plane-polarization by absorbing the light of opposite polarization, which amounts to nearly half the total light. Also, this material is not attractive, since it is tinted a rather unattractive greenish- or brownish-gray and is transparent, revealing the bare sources.

In 1959, Marks[4] announced the invention of a radically different polarization material which had none of these disadvantages when used in ceiling-mounted light sources. This material is the multilayer polarizer, which achieves plane-polarization by reflection rather than absorption. Light reflected from a flat surface will be horizontally plane-polarized; hence, light transmitted will be preferentially vertically plane-polarized. The selective effect may be magnified by piling up reflecting surfaces, and nearly pure vertically plane-polarized light can be achieved in this manner. Little if any light is lost, since the light which is reflected horizontally plane-polarized may be depolarized by a suitable back plate and reflected for another and yet another chance to pass through the multilayer sheet. This is known as the "reflux principle."

The multilayer polarizer can be made without tint, and it can be diffused so that it is translucent but not transparent, allowing light to be emitted without allowing the light sources to be seen directly. Most important, this material provides vertically plane-polarized light at all points in the room. The light emitted from each source may be thought of as consisting of cones having the same degree of vertically plane-polarized light. The extent to which the light is vertically polarized depends upon the diameter of the cone. Light coming down from a source in a cone of small diameter has the least vertical polarization. The maximum degree of vertical polarization falls in a cone whose radius makes an angle of about 60° with the source.

Let us consider the visual benefits which result from the use of these new multilayer polarizers on ceiling-mounted light sources. We will consider their effects upon the ease of seeing, the comfort and the pleasantness of lighting.

Polarized Light and Ease of Seeing

We have already suggested that vertically plane-polarized light increases the ease of seeing by removing to some extent the veiling reflection produced by ceiling-mounted light sources. As reported in detail in Reference 2, this beneficial effect occurs for all visual tasks studied thus far, regardless of details of the lighting system or the angle at which the task is viewed. Thus, we may say simply that vertically plane-polarized light increases ease of seeing with respect to unpolarized light, ray for ray. We may next demonstrate the method for evaluating the visual significance of this increase in the ease of seeing.

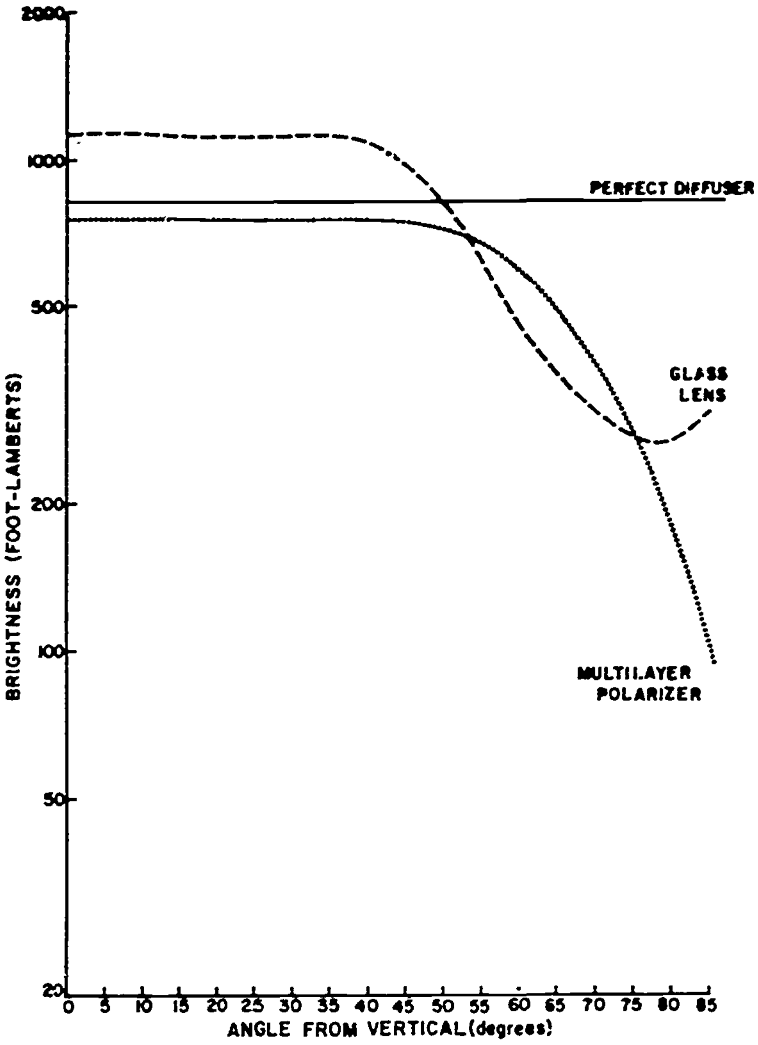

Fig 2:
Brightness characteristics of lighting panels, showing wide-angle brightness reduction of both glass lens and multilayer polarizer panels

The author's 1958 study resulted in a general curve which describes the operating characteristics of human vision, presented as the curved solid line in Fig 1. This is usually called the "standard performance curve" and is the basis for the recommended foot-candle levels adopted by the IES in 1958. Additional illumination increases ease of seeing by enabling the eye to see with less contrast, where contrast is the percentage brightness difference between the task detail and its background. The curve tells us how much illumination we require to see tasks with different physical contrasts. The scales are logarithmic, which means that equal distances on the curve axes correspond to equal percentages. At the levels of modern interior illumination, nearly 15% more illumination is needed to see a task with 1% less contrast. Thus, additional illumination is an ineffective way of improving the ease of seeing, but until the author's recent study of reflected glare was completed, it was considered the *only* way. The recent work has shown clearly that different lighting systems actually produce considerably different values of task contrast. This means that lighting can affect ease of seeing in two ways: by the *direct* effect of producing more task contrast; and by the *indirect* effect of altering the operating characteristic of the eye, to allow it to see less contrast.

The two methods of increasing ease of seeing are shown by the two arrows in Fig 1. Assume a lighting system that produces task contrast, C_o, and illumination, E_o. The open circle shows this combina-

tion as falling below the standard performance curve, indicating that the task is too difficult visually. To reach the standard level of vision represented by the curve, we may either increase contrast to the value C_1 (as represented by the vertical arrow) or increase illumination to E_1 (as represented by the horizontal arrow). Now, from the point of view of ease of seeing, a lighting system which produces contrast C_1 and illumination E_0 is equal to one which produces contrast C_0 and illumination E_1. Therefore, the quality of illumination which increases C_0 to C_1 has the *visual effectiveness* of illumination equal to E_1 although a foot-candle meter reads the illumination level E_0. The *Visual Effectiveness Factor* (VEF) of this illumination is E_1/E_0. The system has a Contrast Factor (CF) equal to C_1/C_0. When the CF is 1.087, the VEF is 2.000. This means that a lighting system which is able to increase task contrast by 8.7% increases ease of seeing as much as one which *doubles* the foot-candle level provided by the first system. This arithmetic is fully accepted by lighting engineers [5] and means that *quality* of lighting is much more important than *quantity*, even so far as ease of seeing is concerned. An 8.7% increase in task contrast

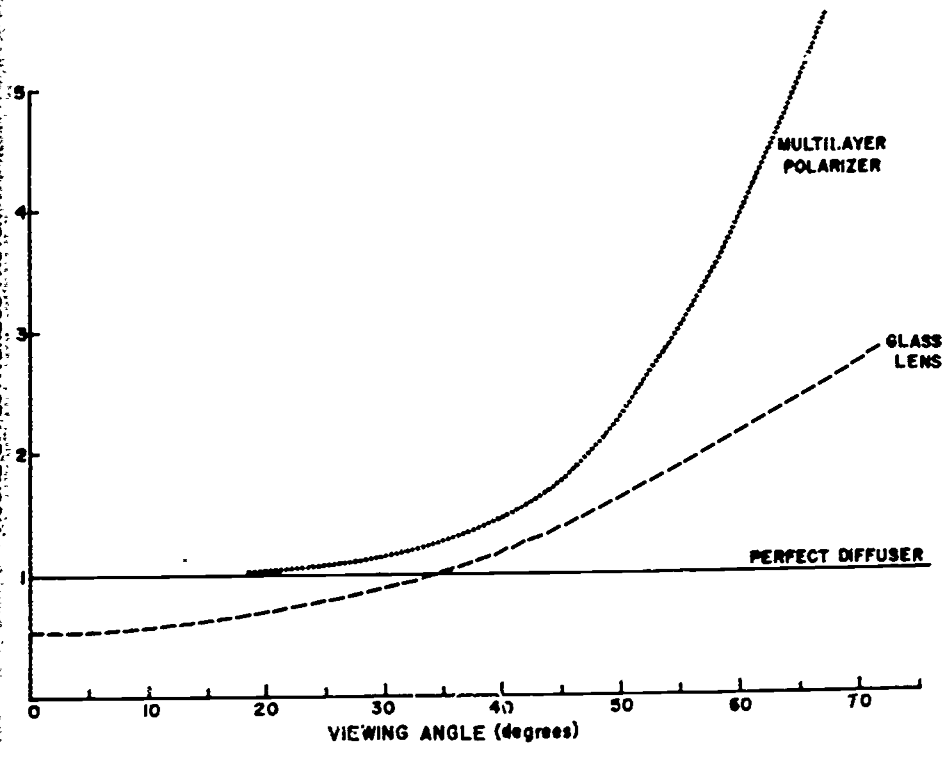

Fig 3:
Visual effectiveness of lighting panels when illuminating a pencil task viewed at different angles from straight down

is actually not very obvious to the unskilled observer. But then, neither is the change in ease of seeing produced by doubling the foot-candle level. Thus careful laboratory and field methods are required to evaluate the ease of seeing produced by various lighting systems.

We may next consider what principles of lighting can be used to increase task contrast. Task contrast actually depends upon the strength and polarization of each light ray, and therefore depends upon location and size of ceiling-mounted light sources in a complex manner. An adequate treatment of this problem will be found in other articles by the author.[6] Here, let us consider only what effect lighting *materials* have upon task contrast.

The light rays which produce the *least* task contrast are those which come from what is called the specular angle. That is, there is a point on the ceiling which is the terminus of a line directed downward from the eye to the task and reflected as by a mirror upward toward the ceiling. Task contrast can be improved by minimizing the amount of light coming from this point and from neighboring points on the ceiling. This means that the spatial distribution of light coming from each element of the ceiling will influence task contrast to a different extent for each angle at which a task is viewed.

We can analyze the visual effectiveness of materials with known spatial distribution of light by computing the task contrast they will provide.[2] Fig 2 shows the spatial emission characteristics of three translucent lighting panels. The curves show how the panel brightness varies with the angle at which the panel is viewed, when zero represents looking straight up at the panel. These data are convenient for use in computing the task contrast produced by illumination from these panels. The solid curve is a perfectly diffuse panel which has equal brightness from all angles. The dashed curve is a well-known glass lens panel which cuts off light at wide angles in order to reduce glare discomfort. Essentially the same characteristics are found with plastic lens panels. The dotted curve is a flat multilayer polarizing panel which is available in different plastics such as vinyl, styrene and acrylic. Although this panel was designed primarily to produce vertically plane-polarized light, it also possesses wide-angle brightness cut-off.

Fig 3 shows values of the Visual Effectiveness Factor (VEF) for these materials when used to illuminate a visual task consisting of medium soft pencil on matte white paper. Values are given for various viewing angles, with zero representing the observer as looking straight down at the task. The value of VEF is taken as unity for the perfect diffuser at each value of the viewing angle to serve as a standard of comparison.

Consider first the values of VEF for the lens panel. When the task is viewed straight down, the VEF is about .5. This means that twice as much illumination will be needed with these panels as with perfect diffusers, for equal ease of seeing. The value of VEF increases with size of the viewing angle, reaching unity at about 34° and increasing upward to 2.0 at 58°. This means that when the task is viewed at 58°, only half as much illumination is needed with these panels as with perfect diffusers. Clearly, the light distribution produced by these panels greatly *reduces* ease of seeing for small angles of view and *increases* seeing ease for large angles of view.

Consider next the values of VEF for the multilayer polarizer. The values are about equal to unity for all angles of view up to 18°, and increase markedly to a value of 2.0 when the task is viewed at 47°. The value for 60° viewing is nearly 4.0. This means that for viewing the pencil task at small angles the

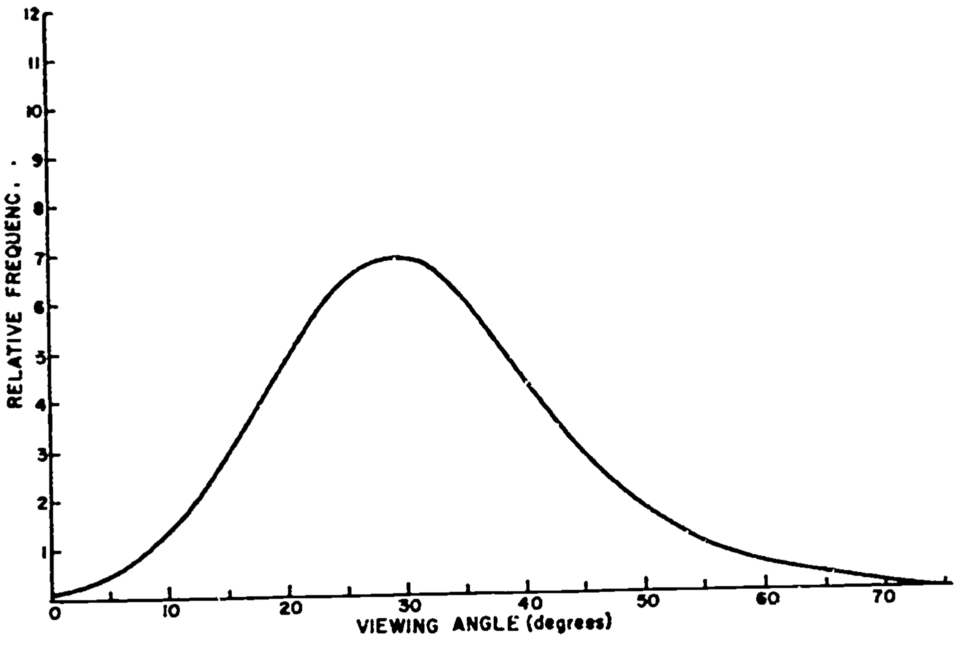

Fig 4:
Frequency of viewing at different angles

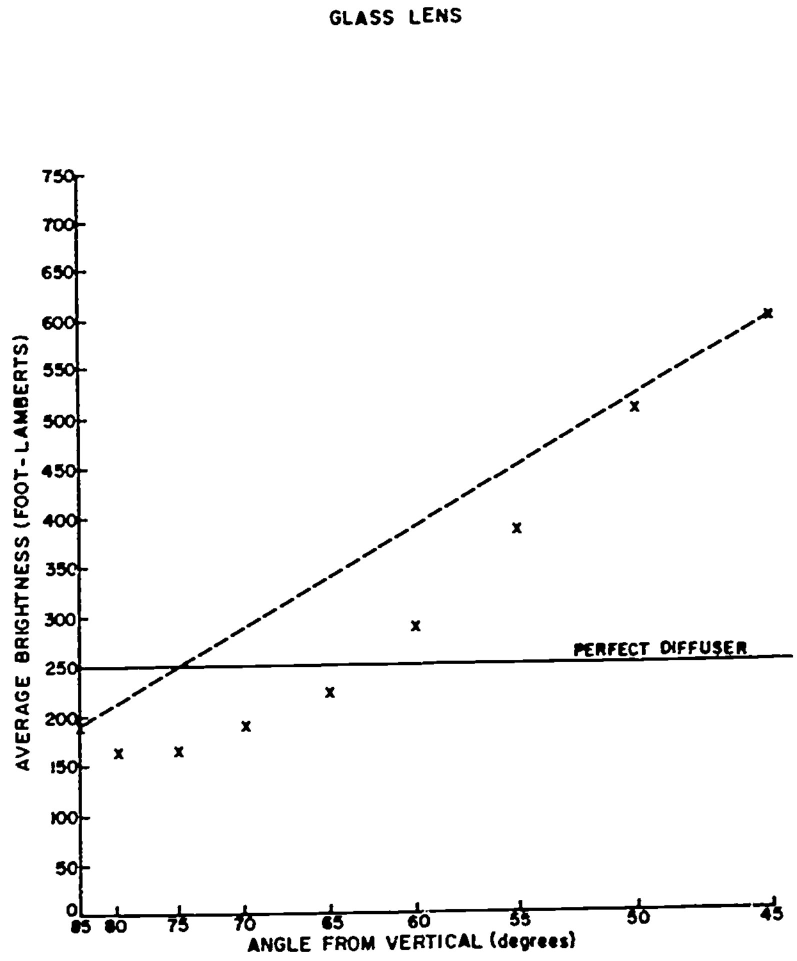

Fig 5:
Brightness characteristics of glass lens panel to meet the Scissors Curve criterion for the reduction of glare discomfort. Dashed line and data points are for the glass lens

illumination level required with these panels is about the same as for perfectly diffuse panels, but only half as much illumination is needed for viewing at 47° and only one quarter as much is needed for viewing at 60°.

Comparison of the data for the lens and multilayer polarizer panels shows rather well the effect of polarization as such, since the two panels have wide-angle brightness cut-off. The effect of polarization is sizable for *all* viewing angles. In effect, when the viewing angle is small, the beneficial effect of polarization is offset by the deleterious effect of the spatial distribution of light (which does, however, reduce glare discomfort).

Fig 4 demonstrates the frequency with which different viewing angles are used.[6] We note that angles are used from 0 to more than 70°, with the mode between 20 and 40°. Thus, the lens panels reduce ease of seeing at the very angles at which vision most frequently occurs. The multilayer polarizer does not improve ease of seeing much for many viewing angles which are frequently used, but it does increase seeing ease substantially for other commonly used angles. If the frequency of different viewing angles is used to weight the values of VEF for the multilayer polarizers, a value of nearly 2.0 is obtained when four different visual tasks are considered and when weight is given to the greater need for improved ease of seeing for tasks viewed at the wider angles.[3] This means that illumination from perfectly diffuse panels would have to be doubled to produce the over-all improvement in ease of seeing made possible by use of multilayer polarizing panels. The interesting and important point to emphasize about the multilayer polarizing panels is that they improve ease of seeing as indicated, without any appreciable loss in luminous efficiency. The visual effectiveness of such panels, and their efficiency in converting lamp lumens into foot-candles, are revealed jointly by the adjusted VEF. This is an index which for the first time summarizes the effectiveness of a lighting material in aiding vision, taking account of both the *quantity* of illumination provided, and the *quality* of this illumination as measured by its ability to provide good task contrast.

Polarized Light and Visual Comfort

The degree of comfort to be expected with lighting systems involving different materials may be evaluated in terms of the Scissors Curve.[7] This curve reflects the fact that the eye can tolerate a greater brightness directly overhead than across the room, the latter being nearer the horizontal line-of-sight. To reduce brightness near the line-of-sight, the material must have the wide-angle brightness cut-off illustrated by both the lens and multilayer polarization panels in Fig 2. The Scissors Curve sets an upper limit on the tolerable brightness at each angle, as shown by the sloping lines in Figs 5 and 6, requiring that a light source be dimmed until it falls below the allowable brightness at *all* angles.

Expressed in these terms, we can only say that a light source does or does not violate the limitations

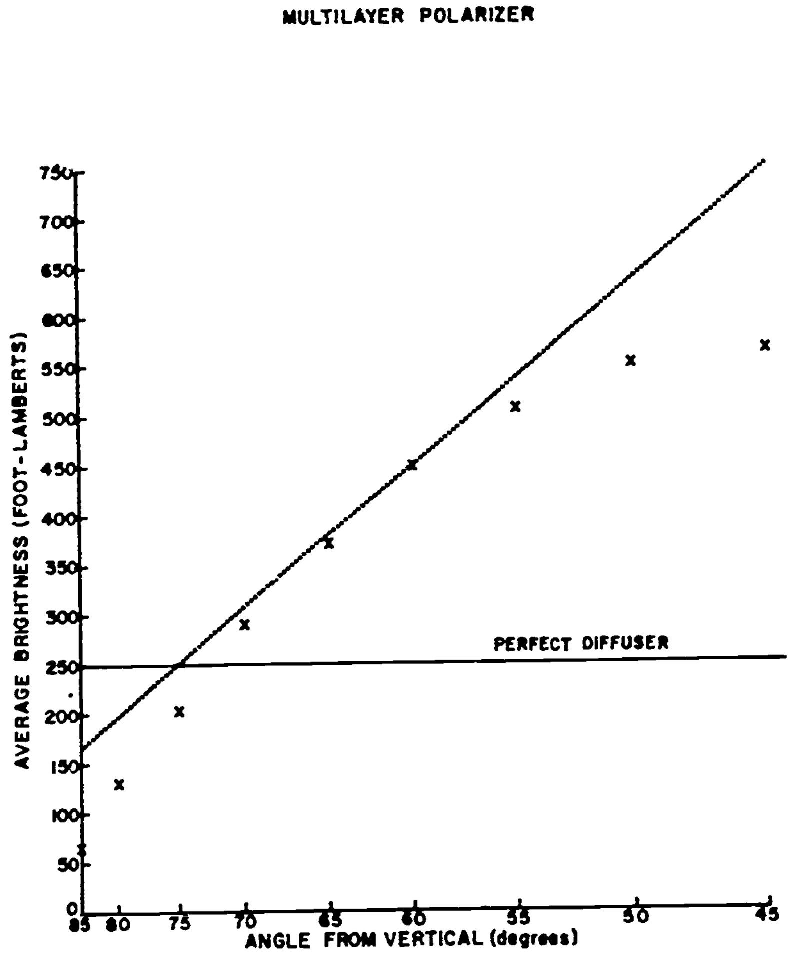

Fig 6:
Brightness characteristics of multilayer polarizer panel to meet the Scissors Curve criterion for the reduction of glare discomfort. Dotted line and data points are for the multilayer polarizer

set by the Scissors Curve, but we cannot compare the abilities of two materials to reduce glare. Of course, we want to provide illumination *without* producing glare discomfort. The author[8] has developed the Index of Comfortable Illumination (ICI), which rates how much illumination a material can provide without discomfort, using a perfectly diffuse panel as a basis of comparison. The values are 2.44 for the glass lens and 2.36 for the multilayer polarization panel. This means that these panels are both so effective in reducing glare discomfort that nearly 2.5 times as much illumination may be used without discomfort as may be used with perfectly diffuse panels. It should be emphasized that the multilayer polarizer has achieved almost as good control of glare discomfort as the glass lens, without losses in ease of seeing for tasks viewed at small angles.

Polarized Light and Pleasantness

As indicated earlier, vertically plane-polarized light always reduces the amount of light-veil reflected from the surface of materials, and therefore reveals to an increased extent the patterns of texture and color in materials. The light-veil is an unfocused image of the light source. Thus, vertically plane-polarized light brings out the essential character of materials from behind the veil contributed by the light source. This effect occurs for all surfaces in a visual environment and for all angles of viewing involved. The use of vertically plane-polarized light therefore increases the purity of colors, particularly those with great saturation, and increases the richness of textures.

To summarize, vertically plane-polarized light produces a fundamental improvement in the ease of seeing, comfort and pleasantness of the visual environment, without appreciable loss in luminous efficiency. The primary effect of vertical polarization is to reduce the light-veil formed by surface reflection of light from ceiling-mounted light sources, thus improving the visibility of task detail to increase ease of seeing, and improving the apparent saturation and textural richness of materials to increase esthetic pleasantness. These effects occur for all ordinary materials used in visual environments, for all surfaces and all viewing angles. As an additional benefit, flat multilayer panels which produce vertically plane-polarized light reduce panel brightness at wide angles, which markedly reduces glare discomfort. No other lighting material produces a comparable increase in task detail, apparent saturation and textural richness for all materials, surfaces and viewing angles. The class of lighting material (the glass or plastic lens panel) which produces a comparable decrease in glare discomfort by means of a wide-angle brightness cut-off decreases task detail and decreases ease of seeing at the viewing angles most commonly used with tasks mounted on horizontal surfaces.

As with any class of useful products, multilayer polarizers may be made with high or low effectiveness. Multilayer polarizing panels should be certified with respect to the Visual Effectiveness Factor (VEF) and Index of Comfortable Illumination (ICI), as well as with respect to their effectiveness in providing illumination from lamp lumens.

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